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16. ABSTRACT

The National Crop Loss Assessment Network (NCLAN) is a group of organizations cooperating in research to assess the short- and long-term economic impact of air pollution on crop production. The primary objectives are 1) to define relationships between yield of major agricultural crops and doses of ozone, sulfur dioxide, nitrogen dioxide and mixtures of these pollutants and 2) to used these relationships to assess the economic consequences of exposure of crops to ambient levels of these pollutnants throughout the United States. The economic assessment effort will include developing methods to extrapolate NCLAN dose-response relationships to estimate regional and national yield losses and estimates of the economic impact of yield losses on producers and consumers. This is the third annual NCLAN report, covering the period from 1 February 1982 to 31 January 1983. During this period, there was increased emphasis on studies to measure ozone dose-plant response relationships. This was accomplished for winter wheat at two regional sites, and for kidney bean and grain sorghum. Dose-response relationships for ozone and sulfur dioxide, singly and in mixtures, were determined for tomatoes and cotton. There was increased research on the effects of factors which may influence pollutant dose-yield soybeans exposed to ozone or to mixtures of ozone and sulfur dioxide and for cotton exposed to sulfur dioxide. Ozone additions to ambient ozone levels were constant at Beltsville, Argonne, Raleigh, and Ithaca, and were proportional to ambient ozone levels at Shafter and Tracy.

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ABSTRACT

The National Crop Loss Assessment Network (NCLAN) is a group of organizations cooperating in research to assess the short- and long-term economic impact of air pollution on crop production. The primary objectives are 1) to define relationships between yield of major agricultural crops and doses of ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and mixtures of these pollutants and 2) to use these relationships to assess the economic consequences of exposure of crops to ambient levels of these pollutants throughout the United States. The economic assessment effort will include developing methods to extrapolate NCLAN dose-response relationships to estimate regional and national yield losses and estimates of the economic impact of yield losses on producers and consumers.

This is the third annual NCLAN report, covering the period from 1 February 1982 to 31 January 1983. During this period, there was increased emphasis on the studies to measure O_3 dose-plant response relationships. This was accomplished for winter wheat at two regional sites, and for kidney bean, and grain sorghum. Dose-response relationships for O_3 and SO_2, singly and in mixtures, were determined for tomatoes and cotton. There was increased research on the effects of factors which may influence pollutant dose-yield response relationships. The influence of soil moisture was studied for soybeans exposed to O_3 or to mixtures of O_3 and SO_2, and for cotton exposed to SO_2. Ozone additions to ambient O_3 levels were constant at Beltsville, Argonne, Raleigh, and Ithaca, and were proportional to ambient O_3 levels at Shafter and Tracy. The effects of relative fluctuations of O_3 concentrations (constant vs proportional additions) was studied for soybeans at Raleigh.

In addition to polynomial functions, the Weibull analysis (Section 4.1) was used to describe dose-response relationship. The Weibull is of interest because of its flexibility, its biological relevance, and its ability to describe combined relationships involving more than one cultivar.

At all sites, accepted NCLAN quality assurance protocols were followed for cultural and biological measurement practices. Independent audits showed that all sites met acceptable criteria for pollutant monitoring.

In studies with O_3-SO_2 mixtures no significant interactive effects on yield occurred. Soil moisture changed O_3 dose-response relationships in two studies with soybeans but not in another with cotton. Dose-response relationships for 'Davis' soybeans were not significantly different when O_3 additions were constant or proportional to ambient O_3 levels. Sulfur dioxide at present or anticipated ambient doses did not significantly decrease yield in any of the studies.

The 1982 dose-response results indicate that O_3 at ambient levels (seasonal 7 h per day mean of 0.03 to 0.06 ppm) can cause yield losses of most of the crops studied when compared to yield at 0.015 to 0.025 ppm. A seasonal mean of 0.043 ppm caused a 33% loss of winter wheat cv 'Vona' at Ithaca but 0.041 ppm caused losses of only 1% for winter wheat (cv 'Roland,' 'Abe,' and 'Arthur 71' combined) at Argonne. Kidney bean yield was decreased by 17% at 0.052 ppm (Ithaca), tomato yield was decreased by 6% at 0.033 ppm (Tracy), and cotton yield was decreased by 11% at 0.058 ppm (Raleigh).

The response of 'Williams and Forrest' soybeans to ambient O_3 was greatly affected by soil moisture at Beltsville. Plants with some moisture stress for part of the season were more sensitive to ambient O_3 levels than those with no moisture stress. Measured yield of grain sorghum (Argonne), barley (Shafter), and soybean (Raleigh) were not affected by levels of O_3 at or slightly less than ambient.

Estimates of O_3 doses during the growing season in agricultural areas were made for the years 1978 through 1982 using available monitoring data and the interpolation/extrapolation method called kriging. A strong correlation was shown between the seasonal 7 h per day (0900-1600 h) mean and the daily hourly (0900-1600 h) peak mean. Relationships between the seasonal 7 h per day mean and the single seasonal peak concentrations were erratic.

A crop simulation model was used to provide a preliminary estimate of regional losses of soybean yield in Illinois and Indiana due to O_3. The model was interfaced with weather and O_3 doses. More data will be required to estimate the effects of moisture stress on O_3 dose-response relationships.

Progress toward a national economic assessment was made. The focus was on determining the magnitude of potential sensitivity of the assessment to uncertainties in the response data and what affect this could have on the credibility of the assessments. Economic assessments were performed using data from linear and Weibull models. Estimates of corn yield changes at alternative O_3 levels using the Weibull model were larger than those predicted by the linear model. The reverse was true for soybeans and winter wheat.

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SECTION 1

INTRODUCTION

The current ozone (O_3) and sulfur dioxide (SO_2) secondary National Ambient Air Quality Standards (NAAQS) are based on vegetation effects information presented in the Air Quality Criteria for Ozone and Other Photochemical Oxidants (USEPA, 1978) and the Air Quality Criteria for Sulfur Oxides (USEPA, 1973). These reviews illustrated a need for additional field studies of the effects of exposure on economically important crops to support evaluation of the economic impact of O_3 and SO_2 on agriculture.

The National Crop Loss Assessment Network (NCLAN) is a nationally coordinated program of field and laboratory studies, crop modeling, and economic assessment initiated by EPA to address the significance of crop losses caused by air pollution. Its research is directed toward answering the following two questions:

1. What biological effects occur at various pollutant levels in the ambient environment?

2. How economically significant is the effect?

The program addresses question 1 by developing dose-response data which quantitatively describes the relationship between exposure dose and biological response for important crop species. Question 2 is addressed by incorporating the dose-response data into economic models which permit estimation of the national economic consequences of these effects.

The program has focused on effects of O_3 on agronomic crops and the economic significance of these effects. Little information is available concerning O_3 effects on perennials. Likewise, relatively little effort has been directed at effects of SO_2, NO_2, or their mixtures with O_3. These are directions the program could take as the data base for O_3 effects on agronomic crops becomes sufficient.

A Research Management Committee (RMC), representing six air pollution research programs within the U.S. (Table 1.1), plans, manages, and executes the NCLAN Research Plan (Preston, 1982). The program objectives, approach, and organization are discussed in detail elsewhere (Heck et al., 1981; Adams, 1982; Heck et al., 1982a,b; Kohut et al., 1982; Preston, 1982) and will be reviewed briefly.

NCLAN program components (e.g., regional pollutant dose-yield response demonstrations, pollutant/environmental interaction studies, physiological and growth studies, crop model development, and economic modeling) have been coordinated to provide a systematic flow of information needed to conduct a

TABLE 1.1. SITE LOCATIONS, REGIONAL COORDINATORS, AND SENIOR SCIENTISTS.

	Site Location	Regional Coordinator	Senior Scientists
1.	Northeast Regional Crop Loss Assessment Program (NERCLAP)	Leonard Weinstein Boyce Thompson Institute Ithaca, New York	Robert G. Amundson Robert J. Kohut John A. Laurence
2.	Southeast Regional Crop Loss Assessment Program (SERCLAP)	Walter W. Heck, USDA North Carolina State University, Raleigh, NC	William Cure Allen S. Heagle John O. Rawlings
	Beltsville, Maryland		Jesse H. Bennett Howard E. Heggestad
3.	Central States Regional Crop Loss Assessment Program (CSRCLAP)	Joseph E. Miller Argonne National Lab Argonne, Illinois	Lance W. Kress
4.	Southwest Regional Crop Loss Assessment Program (SWRCLAP)	O. Clifton Taylor University of California Riverside, California	Patrick Temple
5.	Northwest Regional Crop Loss Assessment Program (NWRCLAP)	Eric M. Preston Environ. Prot. Agency Corvallis, Oregon	Richard M. Adams Grady Neely

national economic assessment of the effects of air pollutants on U.S. agriculture. A network of five field test sites (Ithaca, NY; Beltsville, MD; Raleigh, NC; Argonne, IL; Shafter, CA) have been established in regions (Northeast, Southeast, Central States, Southwest) that contribute significantly to the production of the major crops and have actual or potential pollution problems. At these test sites, normal crop cultural conditions are maintained under ambient and simulated regimes of known air pollution levels.

Thus far, the NCLAN field experiments have concentrated on completing O_3 dose-response data sets for the crop species of greatest economic importance. Data sets have been generated for corn, soybean, winter wheat, cotton, grain sorghum, barley, tomato, peanut, and dry bean which rank 1, 2, 4, 5, 7, 9, 11, 12, and 15, respectively, in economic importance.

Table 1.2 summarizes the O_3 dose-response data which will be available from NCLAN and other sources after the 1983 growing season. Though the O_3 dose-response data base is now substantial, past research in NCLAN (Table 1.3) and elsewhere has shown that genetic and environmental factors may affect plant response. Extrapolation of the site-specific dose-response data to estimate regional level yield changes introduces a number of uncertainties which cannot yet be quantified. Many cultivars of each crop species are grown in a region. The dose-response data include from one to a few of these. Potential extrapolation errors are introduced because the quantitative response of cultivars within a species can be different. The degree of difference in relative sensitivity among cultivars can be estimated experimentally. Thus far, this has been done in the field only for corn. However, dose-response curves have been developed for six cultivars of soybean and four cultivars of wheat. Some cultivars have been evaluated in two different growing seasons. Thus, a preliminary evaluation of between-year and among-cultivar response differences is also possible for soybean and wheat. Use of the Weibull function (discussed in Section 4.1) for modeling dose-response may permit development of combination models which incorporate inherent variation in species response among sites, years, and cultivars.

A second significant source of extrapolative uncertainty results from insufficient quantitative information describing how the dose-response to O_3 may be changed by changes in plant water status. Preliminary experiments with cotton and soybean have provided mixed results. The interaction of water stress with O_3 response appears to be complex and will require substantial additional reearch to determine its potential consequences for NCLAN's economic assessments.

Ideally, dose-response data for those crops that are usually not irrigated should be collected under several soil moisture regimes. These data would allow consideration in the yield loss estimates of the potential impact of regional variations in soil moisture. Since this approach would be very costly, NCLAN is addressing the problem with a series of intensive laboratory studies aimed at understanding the nature of the air pollution response to soil moisture level. Selected field experiments will be conducted concurrently to validate the laboratory studies. This approach will allow modeling of the modifying effect of soil moisture on O_3 dose-response.

TABLE 1.2. CROPS AND CULTIVARS FOR WHICH NCLAN HAS DEVELOPED O_3 DOSE-RESPONSE DATA.

	Crop Coverage	
Crop/Cv.	% of Total Acreage	Sites and Year Grown
Corn		
Pioneer 3780	23	Argonne, Illinois (1981)
PAG 397		Argonne, Illinois (1981)
Soybean		
Hodgson	20	Ithaca, New York (1981)
Davis		Raleigh, North Carolina (1981, 1982)
Williams		Beltsville, Maryland (1981, 1982)
Essex		Beltsville, Maryland (1981)
Corsoy		Argonne, Illinois (1980)
Forrest		Beltsville, Maryland (1982)
Wheat	18	
Vona		Ithaca, New York (1982)
Arthur		Argonne, Illinois (1982)
Abe		Argonne, Illinois (1982)
Roland		Argonne, Illinois (1982)
Cotton	4	
Acala SJ2		Shafter, California (1981, 1982)
Stoneville 213		Raleigh, North Carolina (1982)
Grain Sorghum	5	
A28+		Argonne, Illinois (1982)
Barley		
Poco	3	Shafter, California (1982)
Peanut		
NC-6	2	Raleigh, North Carolina (1980)
Tomato		
Jet Star	<2	Beltsville, Maryland (1980)
Murietta		Tracy, California (1981, 1982)
Kidney Bean		
California Light Red	<1	Ithaca, New York (1980, 1982)

TABLE 1.3. NCLAN FIELD EXPERIMENTS ILLUSTRATING THE EFFECTS OF GENETIC AND ENVIRONMENTAL FACTORS ON O_3 DOSE-RESPONSE.

Crop/Cultivar	Year	Site
I. Cultivar Sensitivity Rankings		
Corn (14 hybrids)	1981	Argonne, Illinois
II. Interactions Between O_3 and Soil Moisture		
Cotton Acala SJ2	1981, 1982	Shafter, California
Soybean Williams, Forrest	1982	Beltsville, Maryland
III. Interactions Between O_3 and SO_2		
Cotton	1982	Raleigh, North Carolina
Tomato	1981, 1982	Tracy, California
	1981	Beltsville, Maryland
Soybean	1981	Raleigh, North Carolina
	1981, 1982	Beltsville, Maryland

Other air pollutants may interact with O_3 to modify dose-response. Experiments to date (Table 1.3) suggest that while this interaction may be statistically significant, it is not likely to alter response as much as the water stress interaction. Therefore, further study of these effects will receive lower priority than the water stress interaction.

Though the basic NCLAN dose-response data (Table 1.2) will be sufficient to conduct a preliminary assessment of the national consequences of O_3 to U.S. agriculture, two important and incompletely tested assumptions will be required in extrapolation the biological data. These are that (1) all economically important varieties of species respond similarly (in aggregate) to those tested and (2) environmental conditions differing from those in the field experiments would not significantly affect the aggregate estimate of plant response to O_3. The consequences of these assumptions for a national economic assessment are as yet unclear. Substantial effort in FY83 will be devoted to evaluating these.

During 1982, regional assessments of the economic impact of O_3 on Midwest and California agriculture were completed. In 1983 a preliminary attempt will be made to estimate the national economic consequences of O_3 to U.S. agriculture. Because effects of genetic and environmental factors on crop response to O_3 are incompletely understood, the results will be interpreted with caution. Refinements in the biological data base should allow more definitive assessments in future years.

In this report, results of 1982 research are presented. Section 4 presents biological dose-response data for O_3 and data concerning modification of these responses by environmental variables. Section 5 discusses the effort to apply these data to evaluation of the economic consequences of air pollution for U.S. agriculture.

SECTION 2

CONCLUSIONS

WINTER WHEAT RESPONSE TO O_3 (Ithaca, New York; Argonne, Illinois)

The winter wheat cultivar 'Vona' appears to be more sensitive than others. Seven h/day mean O_3 cocentrations of 0.043, 0.061, 0.077, or 0.096 ppm from 18 May to 17 July caused measured seed yield reductions of 33, 56, 68, and 73%, respectively, compared to yield at 0.021 ppm O_3. This is the first report of a loss of this magnitude from exposure to ambient O_3 levels. The 56% reduction at 0.064 ppm was caused without exceeding an hourly mean of 0.109 ppm. The major effect of O_3 was on seed size rather than seed number.

At argonne, Illinois, the cultivars 'Abe,' 'Arthur-71,' and 'Roland' were exposed to O_3 for 7 h/day from 8 May to 2 July. For the cultivars combined, measured yield loss at 0.041, 0.068, 0.095, and 0.122 ppm was 1, 19, 37, and 48%, respectively, compared to that at 0.023 ppm. This study also showed that losses were related mainly to seed size rather than to seed numbers.

KIDNEY BEAN RESPONSE TO O_3 (Ithaca, New York)

Red kidney bean, 'California Light Red,' was exposed to O_3 for 7 h/day on 42 days between 11 August and 6 October. Stomatal conductance and total shoot and pod biomass decreased as O_3 concentrations increased. The biomass effects were first noticed after about 3 weeks of exposure. Statistical analyses showed that O_3 dose-yield-response relationships were not affected by removing some plants for growth analyses during the season. Measured seed yields at 0.040, 0.052, 0.073, and 0.087 ppm were 1% greater, and 17, 38, and 48% less, respectively, than yield at 0.023 ppm.

BARLEY RESPONSE TO O_3 (Shafter, California)

'Poco' barley was planted in November and exposed to O_3 on 23 days between 16 February and 2 April. A significant relationship between O_3 dose and yield was not established at concentrations ranging from 0.020 to 0.094 ppm. This cultivar of barley appears to be relatively resistant to O_3.

RESPONSE OF GRAIN SORGHUM TO O_3 (Argonne, Illinois)

Grain sorghum, 'DeKalb A28+,' was more resistant to O_3 than all other crop species tested in the NCLAN program. Plant were exposed for 7 h/day from 16 July to 8 October. Injury was caused by O_3 only at seasonal means of 0.102 ppm or greater. The threshold O_3 concentration for effects on sorghum yield was similar to that for field corn but sorghum was more resistant than field corn once the threshold was exceeded. If other cultivars of sorghum are as resistant as 'DeKalb A28+,' sorghum appears to be safe from effects of O_3 at current or project ambient levels.

TOMATO RESPONSE TO O_3 AND SO_2 (Tracy, California)

A two-year study with the tomato cultivar 'Murietta' was completed in 1982. O_3 and SO_2 both caused decreased yield but there was no significant interaction between the two pollutants. Ambient levels of O_3 (0.033 ppm seasonal 7 h mean) caused a 3% yield loss in 1981 when weather was normal and a 6% loss in 1982 when the weather was unusually cool and wet. Levels of SO_2 likely to occur in ambient air did not affect yield of 'Murietta' tomato.

COTTON RESPONSE TO O_3 AND SO_2 (Raleigh, North Carolina)

The cotton cultivar 'Stoneville 213' was exposed from shortly after emergence until maturity to five concentrations of O_3 and four concentrations of SO_2, singly and in mixtures. A comparison of response to O_3 was made for chambers with and without frusta (truncated cones) attached. There were no interactions between O_3 and SO_2. Results for O_3 were similar whether or not frusta were used. O_3 at seasonal 7 h/day means of 0.059, 0.072, 0.085, and 0.104 ppm caused decreases in cotton yield of 11, 23, 39, and 55% compared to yield at 0.026 ppm. Sulfur dioxide at present or projected ambient concentrations did not affect cotton yield.

SOYBEAN RESPONSE TO O_3 AND SO_2 AT TWO LEVELS OF SOIL MOISTURE (Beltsville, Maryland)

'Williams' and 'Forrest' soybeans were exposed to mixtures of O_3 and SO_2 for 81 days while maintaining two levels of soil moisture for part of the season. SO_2 did not affect the O_3 dose-response relationships but soil moisture did. For the cultivars combined in plots with relatively moist soil, seed yields at seasonal mean O_3 concentrations of 0.049, 0.078, 0.106, and 0.132 ppm were 3% greater and 18, 29, and 37% less, respectively, than yield at 0.017 ppm O_3. The respective yield losses in relatively dry soil were 29, 31, 32, and 43%. This experiment will be repeated at Beltsville in 1983 to verify these results.

SOYBEAN RESPONSE TO O_3 AT TWO LEVELS OF SOIL MOISTURE (Ithaca, New York)

'Hodgson' soybeans were grown in a greenhouse and exosed to O_3 at two levels of soil moisture. The relationship between O_3 concentration and biomass accumulation was linear at both moisture levels but effects were greater for well watered plants. Relationships shown between O_3 doses and photosynthesis, leaf chlorophyll, leaf sensescence, flowering, and pod formation help to explain mechanisms for O_3-induced yield loss in the field.

COTTON RESPONSE TO O_3 AT TWO SOIL MOISTURE LEVELS (Shafter, California)

This was the second year that 'Acala SJ-2' cotton was tested. Plants were exposed to O_3 from 2 June to 9 September under normal or less than normal irrigation. The cool, humid season in 1982 caused atypical crop develpoment characterized by early boll set. The response to O_3 was affected by moisture stress in 1981 but not in 1982. Plants at both moisture levels were more sensitive in 1982 than in 1981. In 1982, bulk cotton yield at seasonal mean O_3 levels of 0.031, 0.045, 0.065, 0.077, and 0.092 ppm was 0, 15, 43, 45, and

66% less, respectively, than at 0.012 ppm when moisture was adequate. When soil moisture was not adequate, the respective values were 8% less, 3% greater, and 28, 44, and 57% less than at 0.012 ppm.

SOYBEAN RESPONSE TO CONSTANT OR VARIABLE O_3 ADDITIONS (Raleigh, North Carolina)

'Davis' soybeans were exposed to fluctuating ambient O_3 concentration to which O_3 was added in amounts that were constant (0.02, 0.04, or 0.06 ppm) or proportional to ambient (0.33, 0.66, or 0.99 times ambient O_3 concentrations). Dose-response relationships for yield were not significantly changed by the dynamics of O_3 addition. For the constant-addition treatments, measured yield at 0.066, 0.086, and 0.109 ppm O_3 was 24, 32, and 49% less, rspectively, than at 0.019 ppm. For the proportional additions, measured yield at 0.065, 0.081, and 0.092 ppm was 15, 31, and 45% less, respectively, than at 0.019 ppm.

Table 2.1 summarizes crop dose-response functions developed in 1982.

CROP LOSS AND ECONOMIC ASSESSMENT

Kriging (a statistical procedure) was used to estimate rural O_3 levels from the largely urban SAROAD data base. A strong correlation was found between the 7 h seasonal mean and the seasonal mean of daily peaks. Correlation was weak between the 7 h seasonal mean and the highest and second highest peaks of the season. Average O_3 levels generally declined from 1978-1982. Levels are generally higher in the eastern U.S. than in the prairie states.

A simulation exercise demonstrated the feasibility of using simulation modeling to estimate regional crop losses due to air pollutants. Simulation derived dose-response relationships were similar to regression derived relationships for 'Hodgson' soybeans grown in the Northeast.

In 1981, the primary objective of the NCLAN economics program was to define a research strategy which would lead to a defensible assessment of the national economic consequences of O_3 on agriculture by 1985. In 1982, that research strategy was implemented. Specifically, the 1982 economics program consisted of (1) implementation of a series of regional assessments designed to test alternative economic methodologies and (2) a series of statistically based sensitivity analyses designed to answer more pactical questions concerning the degree of precision required in the response data. The regional assessments initiated in 1982 will be completed in 1983. The Corn Belt programming model will serve as a pre-test of the model to be used in the national assessment. The studies performed under item (2) indicate that response function issues such as the use of alternative functional forms of the response to predict yields and the variability in predicted yields (across crop cultivars and experimental sites) can have an effect on the economic estimates. However, use of prior biological information and adequate sample size, as exemplified in the NCLAN experimental design, appears to quickly collapse the range of economic estimates to manageable proportions in terms of choosing between alternative levels of O_3 control.

TABLE 2.1. O_3 DOSE-CROP YIELD FUNCTIONS DEVELOPED BY NCLAN IN 1982.

Crop/cv	Location	Polynomial*	Weibull*
Winter Wheat 'Vona'	Ithaca, New York	$y = 7703 - 124929\ (O_3) + 614583\ (O_3)^2$	$y = 9134 \exp [(-O_3/0.04)^{0.85}]$
Winter Wheat 'Abe'	Argonne, Illinois	---	$y = 5340 \exp [-O_3/0.1432^{2.46}]$
'Arthur 71'		---	$y = 4591 \exp [-O_3/0.1472^{2.34}]$
'Roland'		---	$y = 5451 \exp [-O_3/0.1125^{1.69}]$
Grain Sorghum 'DeKalb A28+'	Argonne, Illinois	$y = 8020 + t\ (-16104\ [O_3 - 0.062]$ if $O_3 < 0.062$, $t = 0$ if $O_3 > 0.062$, $t = 1$	$y = 8137 \exp [(-O_3/0.2963)^{2.22}]$
Cotton 'Stoneville 213'	Raleigh North Carolina	$y = 3723 + 537\ (O_3) - 204500\ (O_3)^2$	$y = 3673 \exp [(-O_3/0.011)^{2.71}]$
Soybeans** 'Forrest'	Beltsville, Maryland	For soil relatively moist, $x = 4584 - 11122\ (O_3)$ For soil relativey dry, $y = 4882 - 16317\ (O_3)$	$y = 4352 \exp [(-O_3/0.171)^{2.75}]$
'Williams'		For soil relatively moist, $y = 5570 - 21566\ (O_3)$ For soil relatively dry, $y = 4406 - 14512\ (O_3)$	$y = 5398 \exp [(-O_3/0.1610)^{1.52}]$
Cotton 'Acala SJ-2'	Shafter, California	$y = 5437 - 418556\ (O_3)^2$	$y = 5351 \exp [(-O_3/0.092)^{2.69}]$
Soybeans 'Davis'	Raleigh, North Carolina	$y = 3566 + 95138\ (O_3) - 2000598\ (O_3)^2$ $+ 9455285\ (O_3)^3$	$y = 4918 \exp [(-O_3/0.121)^{2.26}]$

* Ozone (O_3) concentrations are seasonal (period of O_3 addition) 7 h means (ppm). y = yield (marketable portion) in kg/ha.

** Weibull equations are for the cultivars separately in relatively moist soil. Attempts to fit combined data sets to the Weibull function were not successful.

SECTION 3

RECOMMENDATIONS

NCLAN results from 1980, 1981, and 1982 and results from previous research have shown the need to better understand the effects of factors which can modify O_3 dose-yield response relationships for major crop species. Factors which are thought to be important are: (1) cultivar sensitivity; (2) soil moisture regime; (3) seasonal weather patterns; (4) presence of other pollutants; (5) soil fertility; (6) interactions with parasites and pests; and (7) agricultural chemicals. Confidence in regional and national estimates of pollutant-induced yield loss will be increased in direct proportion to the degree that these interactions are understood.

Priorities for future research include:

(1) Completion of O_3 dose-yield response data sets for several of the economically important crops that remain to be evaluated (tobacco, wheat, barley, and forage crops). By the end of the 1985 field season, we expect to have developed dose-response data for representative cultivars of species accounting for approximately 95% of U.S. field crop acreage.

(2) Evaluation of the potential impact of regional and annual variations in soil moisture on crop loss assessments. This evaluation will include several field experiments designed to characterize the spectrum of response to be expected. Concurrently, intensive laboratory experiments should be directed at elucidating the mechanism of O_3-soil moisture interaction. The interaction should be modeled so that dose-response data developed under irrigation can be appropriately scaled to ambient soil moisture conditions. The model's accuracy could be checked against the results of the field experiments.

(3) Experiments initiated to evaluate the modifying effects of SO_2 exposure on O_3 dose-yield response should be completed (through funding from the Electric Power Research Institute).

(4) Evaluation of the influence of subtle changes in exposure dynamics on O_3 dose-yield response relationships should continue to be evaluated. Preliminary data (Section 4.5) suggest that experimental protocols in which succeeding O_3 treatments are maintained at a constant multiple of ambient concentration produce the same dose-response as protocols in which O_3 treatments are maintaind at a constant increment above ambient. These results need further verification.

(5) Regional economic assessments. These should be undertaken to evaluate alternative assessment methodologies and lay the foundation for a preliminary national-level economic assessment in 1983-1984.

(6) Evaluation of the effect of the manner of characterizing O_3 dose on the the yield response function. NCLAN dose-response data have been presented using the 7 h seasonal mean O_3 concentration as the measure of dose. While this has proven adequate for assessments, its relationship to averaging times used in NAAQS is unclear. An analysis of the effect of alternative expressions of O_3 dose (based on different averaging criteria) on yield response relationships should be undertaken with available NCLAN data.

A summary of field experiments recommended for 1983 is given in Table 3.1.

TABLE 3.1. SUMMARY OF PROPOSED 1983 NCLAN FIELD EXPERIMENTS.

Location	Design	Species/Cultivar
Northeast		
Ithaca, NY	O_3-SO_2-D/R8¶	Winter Wheat, 'Vona'
Southeast		
Beltsville, MD	O_3-D/R**¶	Soybean, 'Corsoy,' 'Williams'
Raleigh, NC	O_3-D/R* **†¶	Soybeans, 'Davis'
Raleigh, NC	O_3-D/R‡	Tobacco, 'McNair 944'
Central States		
Argonne, IL	O_3-D/R¶	Winter Wheat, 'Abe,' 'Arthur'
	O_3-SO_2-D/R	Winter Wheat, 'Abe,' 'Arthur'
	O_3-D/R	Field Corn, 'four genotypes'
	O_3-D/R§¶	Soybean, 'Corsoy'
Southwest		
Shafter, CA	O_3-D/R¶**	Barley, 'CM-72'
	O_3-D/R	Lettuce, 'Empire'

* Growth curve determination in addition to yield.

** Partial or complete experimental repeat. Will measure effects of seasonal environmental differences on dose-response relationships.

† Effects of soil moisture level on O_3 response.

‡ Weekly biochemical assays for O_3 effects on sugar and nitrogen compounds.

§ Effects of constant vs proportional O_3 additions.

¶ Effect of exposure for full season vs exposure for first- or last-half of season.

SECTION 4

RESPONSE OF CROPS TO OZONE

4.1 THE WEIBULL RESPONSE FUNCTION

4.1.1 Introduction

The first set of crop loss frunctions developed for NCLAN was compoased of simple linear equations of the form:

$$\hat{y} = \hat{b} + \hat{b}_1 x$$

where $\hat{y}$ was the predicted yield at 7 h/day seasonal mean O_3 concentration, x; b_0 the intercept at zero O_3 concentration and b_1, the slope. Loss functions were calculated for the 19 available data sets; these, in turn, were converted to percent yield-reduction models relative to an assumed background O_3 concentration of 0.025 ppm. The percent yield reduction equations were than averaged and this average function used to estimate losses for that crop type.

This approach was simple and straightforward; percent yield reductions could be calculated with only knowledge of the O_3 concentration. It did not, however, allow for the nonlinear behavior nor the heteorgeneity that was apparent, even among cultivars of the same species (wheat and turnips).

The Weibull survival function has been adopted to represent both the cultivar (single data set) and crop responses (Heck *et al.*, 1983). The Weibull was selected from among others for primarily biological reasons; the types of data sets generated by NCLAN are generally inadequate for distinguishing among many alternative models. Among other candidate models, such as the quadratic, plateau-linear, or logistic, the Weibull offers several advantages:

1. Its flexible form allows it to cover the entire range of responses observed.

2. It has a biologically realistic form. When the Weibull was used to model the near-threshold response of the two corn cultivars grown at Argonne in 1981, the transition from almost no response to a decreasing yield response was smooth and gradual. A plateau-linear model would require an abrupt change. Use of the Weibull avoids negative yields and percent yield reductions greater than 100%, sometimes encountered with the simple linear models.

3. The 3 parameters used in the Weibull model have reasonably straightforward biological interpretations.

4. With the Weibull, predicted yield at any O_3 concentration is expresed as a proportion of a hypothetic maximum yield at zero O_3 concentration. Since this proportion is independent of the measurement units associated with yield, direct comparisons among the proportional responses of crops and cultivars are possible.

5. The model can be readily extended to include common proportional responses while allowing different levels of yield for different cultivars or species. A second exponential term can be included in the function to accont or effects of a second pollutant with the assumption that the two pollutants act independently but multiplicatively to reduce yield (Heagle _et al._, 1983).

4.1.2 The Weibull Model

The Weibull model used as the basis of the NCLAN crop loss functions is given as:

$$y = \alpha \exp [-(x/\sigma)c] + \varepsilon$$

where y is the yield in appropriate units; α is a parameter representing the maximum yield at zero O_3 concentration in the same units as y; x is the O_3 dose expressed as the seasonal 7 h/day mean in ppm, σ, in ppm, is a parameter representing the O_3 concentration at which $y = \alpha e^{-1} = 0.37\alpha$; and c is a dimensionless shape parameter. The proportion of the maximum yield, α, remaining at any given O_3 concentration is termed the relative response and is given by $\exp [-(x/\sigma)c]$.

4.1.3. Crop Loss Functions -- Single Data Sets

Weibull models were fit to 26 separate data sets representing NCLAN experiments from the 1980 and 1981 growing seasons, as well as some earlier work at the Raleigh site that followed general NCLAN protocols. Though in most cases the yields from the plants in the ambient air plots without chambers were not significantly different from those growing in chambers and receiving the same O_3 dose, the crop loss functions were determined by only teh data from the chamber-covered plots.

When several cultivars were planted in a split plot type of design, crop loss functions were fit to each cultivar separately (wheat, turnips, soybean cultivars Essex and Williams, and corn cultivars PAG 397 and Pioneer 3780).

4.1.4 Significance of Chamber Effects

To determine the impact of the chamber on yield, the Weibull model was expanded to include a chamber effect, α_2:

$$y = (\alpha_1 + \alpha_2 \cdot CH) \exp [-(x/\sigma^C] + \varepsilon$$

All terms have the same interpretation except that CH is a dummy variable equal to 0 if the yield was from am ambient air plot and 1 if from a plot covered with a chamber. $(\alpha_1 + \alpha_2)$ is the maximum yield at zero O_3 for chamber-covered plots; α_1 is the yield at zero O_3 concentration for the ambient air plots. Thus, α_2 is the chamber effect. The significance of α_2 was tested with a t-test.

4.1.5 Combination of Weibull Models -- Crop Models

In an effort to minimize the number of different dose-response equations needed, homogeneity of the proportional response part of the Weibull model was tested over cultivars or other treatment factors within each crop species. This was accomplished by expanding the Weibull model to include a series of α's, one for each component data set, but requiring all to have the ame α and c to enforce the common proportional response.

A weighted nonlinear least-squares procedure was used to estimate the common Weibull equation where each component data set was weighted by the inverse of the standard deviation that had been estimated from its analysis of variance error mean square. This gives equal weight to each data set in estimating the common α and c. Otherwise, because of large differences in error variances due either to scaling differences or large yield differences, certain data sets would dominate the parameter estimates.

The F-test of homogeneity over data sets of the proportional response was a composite set of hypothesis of homogeneity of all of the α's and all of the c's in the individual data sets being combined. F thus has 2(S-1) degrees of freedom for the numerator where S is equal to the number of sets being combined (true only when the univariate Weibull model is used). The denominator of the F-test was the pooled analysis of variance error mean square from a weighted analysis using the weights defined above.

4.2 RESULTS OF O_3 DOSE-RESPONSE STUDIES

4.2.1 Response of Winter Wheat to Chronic Exposure (NERCLAP)*

4.2.1.1 Introduction

Winter wheat is a major crop in the United States comprising over 43 million acres with an annual value to producers of over $6 billion (USDA, 1980). Since wheat is widely grown, it is potentially subject to elevated O_3 concentrations in portions of its range. Little is known of the impact of O_3 on wheat production under field conditions. Shannon and Mulchi (1974) evaluated the response of wheat yield to acute O_3 exposures during anthesis and Phillips and Runeckles (1974) assessed the effect of chronic O_3 exposures on wheat biomass. Heagle et al. (1979) exposed 11 wheat cultivars to O_3 to determine their relative sensitivity and conducted long-term field exposures with 4 cultivars to evaluate dose-response relationships. This study was designed to evaluate the growth and yield responses of a hard red winter wheat cultivar to chronic O_3 exposures under field conditions. The cultivar used in the study was Vona. The 25,756 acres of certified Vona seed grown in 1982 comprised approximately 11% of the acreage of certified hard red winter wheat seed for that year (Association of Official Seed Certifying Agencies, 1982).

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* Robert Kohut, Boyce Thompson Institute.

Vona is the second most extensively grown cultivar in Colorado and is in the top three in Oklahoma and the top five in Kansas (M. Brick, personal communication).

4.2.1.2 Materials and Methods

Cultural practices. Winter wheat (Triticum aestivum cv. 'Vona') was planted with a drill on September 30, 1981, at a rate of 112 kg of seed per hectare in rows 17.5 cm apart. In April 1982 the field was top-dressed with 10-10-10 (NPK) fertilizer at the rate of approximately 220 kg/ha. Stand density during the O_3 treatment was approximately 170 tillers/m-row. Plants were sprayed with Karathane on May 21 and 26 to control powdery mildew (Erysiphe graminis). Soil moisture at a depth of 25 cm was monitored with tensiometers to indicate the need for irrigation. Soil moisture remained adequate throughout the study and irrigation was not required. Precipitation during the spring and summer totaled 36.4 cm which was 2.6 cm greater than the 20 year average for this period.

Pollutant treatments and monitoring. In April the winter wheat stand was evaluated for uniform plant density and soil conditions and sites for 24 treatment plots were selected. Treatments were randomly assigned to six plots within each of four blocks. The five O_3 treatments in open-top chambers were charcoal-filtered air (CF), nonfiltered air (NF), and nonfiltered air to which 0.03, 0.06, or 0.09 ppm O_3 was added (designated NF + 0.03, NF + 0.06, and NF + 0.09, respectively). An ambient plot (AA) not enclosed by an open-top chamber comprised the sixth treatment in each block. The O_3 generation, distribution, and monitoring systems were similar to those used in previous NCLAN studies (Kohut et al., 1981) and were based on those developed by Heagle et al. (1979). All chambers were in place and fans operating by May 14. Exposures were initiated on May 18 as the tightly rolled flag leaf was just becoming visible and terminated on July 17 after the kernels were fully ripe and the straw dead. During this period, exposures were conducted daily except when precluded by rain or technical difficulties. Daily exposures were 7 h in duration (1000 to 1700 EDT). Chamber fans were not operated between 2300 and 0500 to facilitate dew formation within the chambers.

O_3 monitoring was conducted with Monitor Labs Model 8410 O_3 monitors. Pollutant monitoring for each chamber was performed on a timesharing basis using an automated sequential sampling system. The O_3 sampling efficiency for each sampling line was determined twice during the study and taken into account during reduction of the O_3 monitoring data. All O_3 monitors were subject to the NCLAN quality assurance program.

Response evaluations. Plants in the chambers were routinely examined for insect and biotic pathogen injury to insure that control measures could be implemented if required. More extensive evaluations of powdery mildew and O_3 injury and measurements of plant growth were obtained on June 15 and July 6. Ten plants in rows adjacent to those to be harvested for yield were selected for assessment. The height of each plant was obtained and the flag leaf removed for evaluation. The percent of the flag leaf with mildew lesions and showing O_3 injury was determined by visual estimation. Flag leaf area was measured with a portable area meter (Lambda Instrument Corporation Model LI-3000).

Two one-meter row sections were harvested from each of the two center rows of each plot on July 22. Plants were clipped near the ground and the heads were cut from the stems and counted. The heads and straw were oven dried at 32°C for 48 hr and weighed separately. The heads were threshed and the dry weight of grain obtained. The dry weights of 100-seed lots of grain were also determined. The moisture content of the grain after drying was approximately 10%. Harvest data was obtained in accordance with the NCLAN quality assurance plan for biological measurements.

Statistical analyses. Injury, growth, and yield data were evaluated using analysis of variance. Dose-response relationships for yield were assessed with regression analysis techniques.

4.2.1.3 Results

Pollutant treatments and monitoring. Ambient air monitoring was conducted for 72 days during the experiment from May 12 through July 22. During this period, exposures were conducted between May 18 and July 17. These periods will be referred to as the monitoring and exposure periods, respectively. During the 61 day exposure period there were 8 days on which there were no O_3 additions due to rain or technical problems.

The highest 1-h ambient O_3 concentration recorded during the monitoring period was 0.088 ppm; the second highest concentration was 0.086 ppm. The average daily 1-h maximum concentration was 0.054 ppm. The 1-h average O_3 concentration of 0.08 ppm was exceeded four times in the ambient environment during the monitoring period.

The 7-h and 24-h average O_3 concentrations for each treatment during the monitoring and exposure periods are presented in Table 4.2.1.1. A review of the 7-h exposure period data showed that charcoal filtration reduced the O_3 level to approximately 50% of that in the ambient air and nonfiltered air treatments. The increments in the O_3-added treatments were slightly below the target values but still provided distinct levels covering a range of concentrations. The highest and second highest 1-h concentrations, the average daily maximum 1-h concentration, and the maximum 7-h concentration for each treatment are presented in Table 4.2.1.2. The number of times that the 1-h O_3 concentrations of 0.08 and 0.12 ppm were exceeded in each treatment are presented in Table 4.2.1.3. Tables 4.2.1.2 and 4.2.1.3 indicate that the NF + 0.06 and NF + 0.09 treatments experienced relatively high single-event O_3 concentrations and numerous occasions on which the 0.08 and 0.12 ppm concentrations were exceeded. Only the 0.08 ppm concentration was surpassed in the AA, NF, and NF + 0.03 treatments. Neither concentration was exceeded in the CF treatment.

Response evaluations. On June 18, 30 days after exposures were initiated, plants were evaluated for height, flag leaf area, and the incidence of mildew, necrosis, and chlorosis on the flag leaf. Table 4.2.1.4 presents the data for these variables and the nature of their relationship to the treatment O_3 concentrations. Although differences in plant height among the treatments were small, there was a significant linear relationship of decreasing plant height with increasing O_3 levels. Evaluation of the flag leaf showed no change in leaf area or incidence of mildew with increasing O_3 levels.

TABLE 4.2.1.1. AVERAGE O_3 CONCENTRATIONS (ppm) FOR EACH TREATMENT IN THE WINTER WHEAT STUDY AT ITHACA, NEW YORK, IN 1982.

Treatment	Monitoring Period*		Exposure Period**	
	7-h	24-h	7-h	24-h
CF	0.021	0.019	0.022	0.020
AA	0.044	0.034	0.044	0.035
NF	0.043	0.033	0.042	0.034
NF + 0.03	0.061	0.039	0.062	0.041
NF + 0.06	0.077	0.044	0.082	0.047
NF + 0.09	0.096	0.050	0.104	0.053

* The monitoring period was from May 12 through July 22.

** The exposure period was from May 18 through July 17.

TABLE 4.2.1.2. HIGHEST AND SECOND HIGHEST 1-H MEAN, THE AVERAGE DAILY 1-H MAXIMUM, AND THE MAXIMUM 7-H AVERAGE O_3 CONCENTRATIONS (ppm) FOR EACH TREATMENT DURING THE MONITORING PERIOD IN THE WINTER WHEAT STUDY AT ITHACA, NEW YORK, IN 1982.

Treatment	Max. 1-h	Second Max. 1-h	Average Daily 1-h Max.	Max. 7-h
CF	0.074	0.067	0.038	0.042
AA	0.088	0.086	0.054	0.074
NF	0.088	0.086	0.054	0.079
NF + 0.03	0.109	0.108	0.074	0.098
NF + 0.06	0.146	0.141	0.094	0.128
NF + 0.09	0.180	0.177	0.118	0.161

TABLE 4.2.1.3. NUMBER OF OCCASIONS ON WHICH THE 0.08 AND 0.12 ppm 1-H AVERAGE O_3 CONCENTRATIONS WERE EXCEEDED DURING THE WINTER WHEAT STUDY AT ITHACA, NEW YORK, IN 1982.

Treatment	Monitoring Period*		Exposure Period**	
	0.08	0.12	0.08	0.12
CF	0	0	0	0
AA	4	0	2	0
NF	7	0	5	0
NF + 0.03	111	0	109	0
NF + 0.06	261	42	256	42
NF + 0.09	314	189	309	186

* The monitoring period was from May 12 through July 22.

** The exposure peroid was from May 18 through July 17.

TABLE 4.2.1.4. WINTER WHEAT EVALUATION AND INJURY DATA FOR OBSERVATIONS MADE ON JUNE 18 AFTER FOUR WEEKS OF O_3 EXPOSURE AT ITHACA, NEW YORK, IN 1982.

Treatment	Plant Height (cm)	Flag Leaf			
		Area (cm^2)	Mildew (%)	Necrosis (%)	Chlorosis (%)
CF	87.5	13.2	6	1	0
AA	87.5	10.7	0	2	10
NF	82.5	11.8	4	1	21
NF + 0.03	80.0	11.3	2	18	71
NF + 0.06	80.0	12.5	1	15	84
NF + 0.09	75.0	10.7	0	20	80

Although the percent of the flag leaf covered by mildew lesions was relatively small, the incidence of lesions appeared greater on leaves lower on the stem. There also appeared to be a greater level of infection of the lower leaves of plants in the chambers than in the ambient plots. O_3-induced foliar injury consisted of necrosis and chlorosis. Significant relationships between O_3 treatment and the incidence of necrosis and chlorosis on the flag leaf were identified. In each of the three O_3-added treatments, the combined incidence of chlorosis and necrosis on the flag leaf was nearly 100%. In contrast, their combined incidence in the charcoal-filtered treatment was only 1%. The wheat cultivar 'Vona' appears to be particularly sensitive to O_3 and readily displays foliar injury at pollutant concentrations above the ambient level of approximately 0.045 ppm encountered in this study. At the second evaluation on July 6, foliar senescence had progressed to such a degree that it was not possible to collect meaningful data.

Harvest data collected for each treatment include straw dry weight, head dry weight, number of heads, grain dry weight, and 100-seed weight. Yield data are presented in Table 4.2.1.5. Compared to the charcoal-filtered air treatment at 0.022 ppm O_3, yield in the nonfiltered air treatment (0.042 ppm) was reduced 33% while that in the ambient treatment (0.044 ppm) was reduced 24%. Although the yields in the ambient plots and nonfiltered air chambers were not statistically different, there was an indication of a possible chamber effect with a yield reduction of 12% in the nonfiltered chambers compared to ambient. Comparisons of the percent reductions for seed dry weight and 100-seed weight in each treatment show that they are similar, although the seed weight reductions are slightly greater. This is an indication that the primary effect of the O_3 treatments was on seed size rather than seed number. The differences in seed size are evident in Figure 4.2.1.1. Analysis of variance for the open-top chamber data (Table 4.2.1.6) indicated that significant treatment effects existed for all harvest variables except number of heads.

Regression analysis was conducted using linear, quadratic, and Weibull models to develop dose-response curves. The dose-response functions produced with the quadratic and Weibull models using the 7-h monitoring and exposure period O_3 concentrations are presented in Table 4.2.1.7.

4.2.1.4 Discussion

The yield responses of the winter wheat cultivar 'Vona' to controlled O_3 exposures indicates that it is quite sensitive to the pollutant. Compared to the charcoal-filtered treatment at 0.022 ppm, yield reductions ranged from 33% in the nonfiltered treatment (0.042 ppm) to 73% in the NF + 0.09 treatment (0.104 ppm). The magnitude of the reduction at 0.042 ppm was particularly striking. In a study conducted with soft red winter wheat, Heagle *et al.* (1979) found the cultivar 'Holly' required exposure to 0.13 ppm O_3 for 7-h per day for approximately one month to obtain a yield reduction of 33%.

Examination of the treatment exposure regimes indicates that major yield reductions occurred under exposure conditions in which the 1-h average concentration of 0.12 ppm was not exceeded. The 56% yield reduction in the NF + 0.03 treatment (0.064 ppm) was produced by an exposure regime in which the maximum 1-h O_3 concentration was 0.109 ppm. In the nonfiltered air treatment

TABLE 4.2.1.5. WINTER WHEAT HARVEST DATA FROM PLANTS EXPOSED TO O_3 AT ITHACA, NEW YORK, IN 1982.

Treatment	Straw wt. (g/m-row)	Head wt. (g/m-row)	Head Number	Seed Weight		100-Seed Weight	
				kg/ha	% Loss	(g)	% Loss
CF	70.7	118.5	124.3	5331.0	--	3.26	--
AA	71.5	96.5	137.8	4049.8	24	2.32	29
NF	60.0	84.2	111.9	3552.1	33	2.47	24
NF + 0.03	64.3	72.0	115.1	2322.3	56	1.77	46
NF + 0.06	51.3	46.3	117.4	1698.8	68	1.41	57
NF + 0.09	43.4	38.8	100.0	1430.0	73	1.30	69

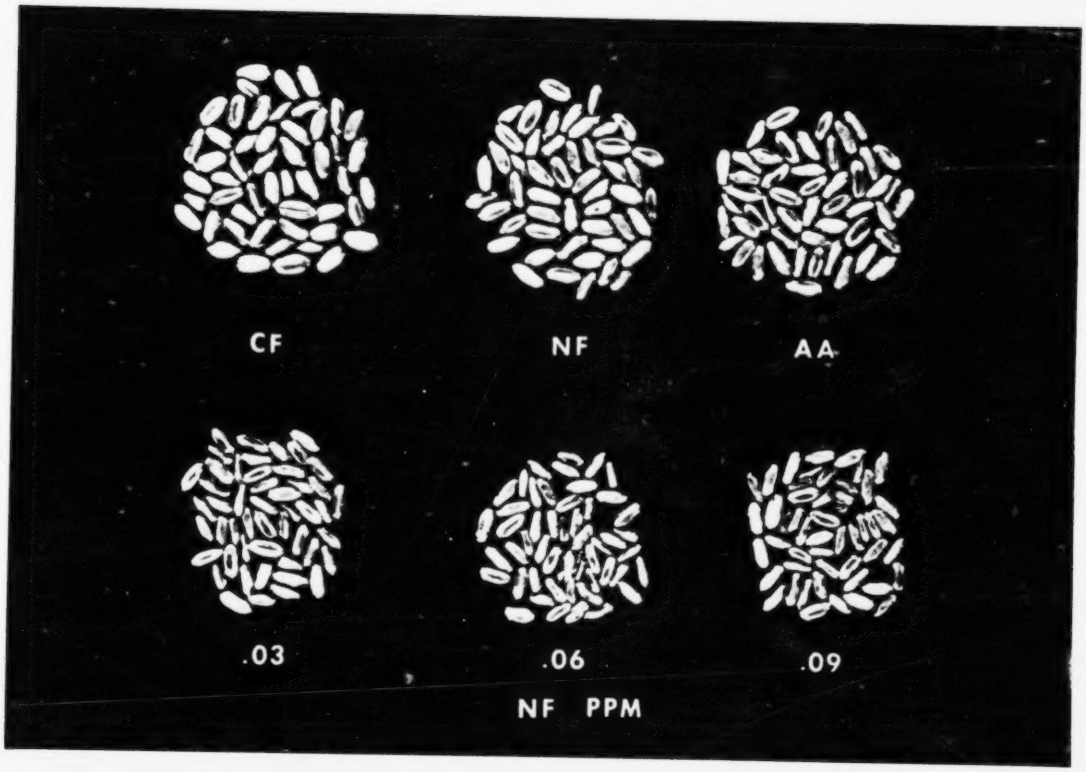

Figure 4.2.1.1. Samples of winter wheat grain harvested from the six O_3 treatments at Ithaca, New York, in 1982. The treatments are charcoal-filtered air (CF), nonfiltered air (NF), ambient air (AA), and nonfiltered air to which 0.03 ppm, 0.06 ppm, and 0.09 ppm O_3 were added.

TABLE 4.2.1.6. ANALYSIS OF OPEN-TOP CHAMBER HARVEST DATA FOR THE WINTER WHEAT STUDY CONDUCTED AT ITHACA, NEW YORK, IN 1982.

Source of Variation	df	Mean Squares				
		Straw Wt.	Head Wt.	Head No.	Seed Wt.	100-Seed Wt.
Block	3	1087.8	2089.2	656.0	559.4	0.12
Treatment	4	1843.1*	16277.8**	1271.4	12550.7**	10.69**
Linear	1	6481.1**	61781.4**	3035.2	44863.4**	38.92**
Quadratic	1	111.1	2433.9*	139.8	5294.2**	3.77**
Cubic	1	96.4	5.6	1909.2	23.0	0.03
Treat x Block	12	300.9	473.3	1231.9	239.8	0.18

F values determined by the ratio of the block or treatment mean square to the treatment x block (error) mean square.

* Pr (value > F critical) = 0.05.

** Pr (value > F critical) = 0.01.

TABLE 4.2.1.7. QUADRATIC AND WEIBULL REGRESSION EQUATIONS FOR WINTER WHEAT YIELD AT ITHACA, NEW YORK, IN 1982. O_3 CONCENTRATIONS ARE THE MONITORING PERIOD (MP) AND EXPOSURE PERIOD (EP) 7-HOUR AVERAGES IN ppm. ALL YIELDS ARE kg/ha.

Quadratic

$\text{Yield} = 7790.0 - 130093.3\ (MP) + 657065.4\ (MP)^2$ $\quad R^2 = 0.90$

$\text{Yield} = 7703.0 - 124928.5\ (EP) + 614582.7\ (EP)^2$ $\quad R^2 = 0.90$

Weibull

$\text{Yield} = 9134.19 \exp -(MP/0.04)^{0.853}$

$\text{Yield} = 9103.82 \exp -(EP/0.04)^{0.853}$

(0.042 ppm) which had a maximum 1-h concentration of 0.088 ppm and in which the 1-h average concentration of 0.08 ppm was surpassed 7 times in the monitoring period, the yield reduction was 33% compared to the charcoal-filtered treatment. The winter wheat cultivar Vona appears to be highly sensitive to O_3 compared to other crops examined by NCLAN.

Head number could be used as a covariate in an anslysis of treatment effect on yield. This analysis might indicate that the seed weight reductions due to O_3 were slightly lower than those presented in Table 4.2.1.5. Comparison of the percent reductions in seed dry weight and 100-seed weight indicates that the major effect of O_3 treatments appeared to be on seed size rather than seed number. This is in agreement with previous wheat research in which acute O_3 exposures during anthesis did not significantly reduce the number of seeds produced per head (Shannon and Mulchi, 1974). If it is assumed that the 100-seed weight is independent of head number and that there was uniform seed set among the treatments, the degree of reduction in the 100-seed weight may be a better estimate of treatment effects on yield. It should be noted, however, that the reductions in seed dry weight and 100-seed weight were very similar.

The two regression models used to produce dose-response functions provided differing fits to the data. With an R^2 value of 0.90, the quadratic model produces good predictions of the treatment mean yield values (Table 4.2.1.3) when the 7-h mean O_3 values are used. In contrast, the Weibull model shows a poorer fit when the treatment means are predicted. The response curve, with a shape parameter (c) of 0.853, indicates a major incremental impact on yield at lower O_3 concentrations and a reduction in the incremental effect at higher concentrations. The steep gradient and concave shape of the response apparently introduces the lack of fit into the lower portion of the dose-response curve. For this particular dose-response, the quadratic function appears to produce a better prediction of O_3 effects on yield.

4.2.1.5 Conclusions

The winter wheat cultivar Vona appears to be highly sensitive to O_3. The yield reductions observed in this study exceed those produced on other wheat cultivars at comparable treatment levels. Vona is most commonly grown in Colorado, Texas, Oklahoma, and Kansas. Although ambient O_3 levels in the rural areas of these states are probably not greatly above background, the apparent sensitivity of this cultivar to O_3 could lead to reduced productivity in certain areas.

4.2.2 Impact of O_3 on Winter Wheat Yield (CSRCLAP)*

4.2.2.1 Introduction

Wheat is the fourth most important crop in the United States in terms of planted acreage (19%) and dollar value (13%). Previous work with four cultivars of soft red winter wheat exposed to O_3 in open-top chambers indicated that yields were reduced from 1-11% at 0.06 ppm O_3 and 11-25% at 0.10 ppm O_3 compared to a 0.03 ppm control treatment (Heagle *et al.*, 1979). Based on the first NCLAN assessment of crop loss due to O_3, winter wheat was more sensitive than field corn and kidney bean and less sensitive than soybean, spinach, head lettuce, peanut, and turnip (Heck et al., 1982). The present study was initiated to provide further biological response data suitable for evaluating ambient air quality standards and for use in the NCLAN economic assessment of the consequences of O_3 exposure to crops. Specifically, the objective was to establish exposure-response relationships between yield of three important cultivars of soft red winter wheat grown in the Midwest and chronic exposures to a range of O_3 concentrations.

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* Lance W. Kress and Joseph E. Miller, Argonne National Laboratory.

4.2.2.2 Materials and Methods

Three cultivars of soft red winter wheat (*Triticum aestivum* L.) ('Abe,' 'Arthur-71,' and 'Roland') were used. These were selected from among the most commonly grown cultivars in the study region after consultation with agricultural extension specialists from the University of Illinois. Previous cropping history of the field site located 40 km southwest of Chicago was soybean (1980) and fallow (1981). The soil at the site is a Morley silt loam, gray-brown podzolic, upland timber soil. This soil has a high water holding capacity, low permeability, and a pH of 5.95 ± 0.24, 5617 ± 884 kg/ha organic matter.

The plot was initially fertilized with 40 kg/ha N and 103 kg/ha P (18-46-0) and the wheat was planted on 13 October 1981. Rows were planted on a 20.3-cm spacing with a grain drill at a predicted rate of 90 kg of seed per ha. The cultivars were planted in alternating rows, so that a particular cultivar occurred in every fourth row. The following spring (11 April 1982) the plot was fertilized with N (50 kg/ha as NH_4/NO_3). Irrigation was not necessary due to slightly above normal rainfall (18.6 cm between 1 May and 3 July).

The experiment was conducted utilizing a randomized complete block design incorporating four replicates of six treatments. The treatments were:

AA, no chamber (ambient air);

CF, charcoal-filtered air chamber;

NF, nonfiltered-air chamber with a small amount of O_3 added to provide a concentration approximating that in the AA plot; and

NF + 0.03, NF + 0.06, and NF + 0.09 in which O_3 was added to NF chambers in sufficient amounts to approximate 0.03, 0.06, and 0.09 ppm of O_3 above ambient, respectively.

The chambers were placed over the plots on 7 May and exposures began on 8 May, shortly after the plants had begun their spring growth and were about 15 cm tall. O_3 additions were terminated 2 July, and the chambers were removed on 13 July, following harvest. When the exposures were terminated, the plants in all treatments had brown leaves, stems, and heads, but the kernels in the CF treatment were still "doughy."

O_3 was generated by silent electric discharge with an OREC Model 03B2-0 O_3 generator. O_3 was measured with Bendix Model 8002 chemiluminescent O_3 monitors calibrated 3-5 times per week on site with a CSI Photocal 3000 (UV) O_3 calibrator. There was one monitor for continuous sampling of ambient O_3, and two monitors to sample 22 field plots (only two of the ambient plots were monitored) on a time share system. Each plot was sampled for 2 minutes and with 11 plots per monitor, each plot was sampled three (occasionally only two) times per hour. During each day the proper functioning of the instruments was checked by comparing the ambient air readings of all three monitors. The efficiencies of the 6.35 mm diameter FEP Teflon sample lines (all 48.8 m long) in transmitting O_3 were measured before and after the experiment, and occasionally spot checked during the experiment in the chambers with a Dasibi 1003 O_3 monitor. O_3 values were subsequently adjusted (5-7%) for line loss. O_3 was not dispensed to the chambers on two full days and five half days due to rain.

Ambient SO_2 was monitored with a TECO Model 43 Pulsed Fluorescent SO analyzer and a Meloy SA 285 Flame Photometric sulfur analyzer. Zero and span checks were made several times per week and multi-point calibrations were performed monthly with a CSI 1700 Gas Phase Titration Calibrator and a standardized SO_2 source.

Two-meter row sections of each cultivar were harvested from the center of each plot on 6-12 July. Grain was hand threshed and cleaned, oven dried to < 1% moisture content (to assure that sample differences were not confounded by differing moisture content) and weighed according to the NCLAN Biological QA Plan. Measurements taken at harvest were number of heads/meter, number of plants/meter (estimated by excavating the root systems), and plant height. Seed weight per one meter of row was adjusted to reflect 14% moisture content and converted to kg/ha. The weight of 100 seeds (100-seed wt) was also obtained for each plot. Seed weight/plant and seed weight per head were calculated. Soil samples obtained at harvest were sent to the Soil and Plant Analysis Laboratory, University of Wisconsin, for analysis of pH, organic matter, P, and K.

An analysis of variance was performed on the yield data using the Statistical analysis System (SAS). An analysis of covariance (by cultivar) was also performed for yield (kg/ha) using number of heads as the covariate. Linear regressions were developed for all chamber treatments using the GLM procedure and Weibull regressions were developed using the NLIN procedure of SAS.

4.2.2.3 Results and Discussion

Pollutant concentrations. The mean seasonal O_3 concentrations (7-h/day mean) from 8 May to 2 July 1982 for the AA, CF, NF, NF + 0.03, NF + 0.06, and NF + 0.09 treatments were 0.042 ppm, 0.023 ppm, 0.041 ppm, 0.068 ppm, 0.095 ppm, and 0.122 ppm, respectively (Table 4.2.2.1). The single highest 7-h value was approximately double the seasonal mean for the AA, CF, and NF treatments, but only 1.69, 1.55, and 1.48 times the seasonal mean for the NF + 0.03, NF + 0.06, and NF + 0.09 treatments, respectively. The seasonal means

TABLE 4.2.2.1. HIGHEST AND SECOND HIGHEST HOURLY O_3 (ppm) MEAN, THE SEASONAL 1-H PEAK, THE HIGHEST 7-H MEAN, AND THE SEASONAL 7-H MEAN, FOR EACH TREATMENT AT ARGONNE, ILLINOIS, IN 1982.*

	7 h/day Values		1 h/day Peak Values		
Treatment	Seasonal Mean	Highest	Seasonal Mean	Highest	Second Highest
AA	0.042	0.084	0.051	0.113	0.095
CF	0.023	0.045	0.031	0.082	0.060
NF	0.041	0.083	0.051	0.120	0.102
NF + 0.03	0.068	0.115	0.083	0.149	0.134
NF + 0.06	0.095	0.148	0.115	0.170	0.169
NF + 0.09	0.122	0.180	0.149	0.220	0.210

* Each value was developed from three (occasionally two) two-minute samples per hour. The mean 1-h and the 7-h values are averages of four replicates.

of the 1-h/day peak values were 21-24% above the seasonal 7-h/day means for all treatments except the CF treatment which was 35% greater. The CF chambers were effective in excluding 40-45% of the ambient O_3.

The seasonal hourly average O_3 data are presented as concentrations that are exceeded for various percentages of the time during the exposure period (Table 4.2.2.2). The ambient O_3 concentrations at canopy level (AA) were generally about 5% lower than those measured at six meters above ground (AA -- 6 m). The NAAQS were violated < 1% of the hours in the NF + 0.03 treatment, approximately 20% of the hours in the NF + 0.06 treatment, and approximately 60% of the hours in the NF + 0.09 treatment.

The daily 7-h and 24-h mean ambient O_3 concentrations between 8 May and 31 October 1982 are shown in Figure 4.2.2.1. The mean seasonal diurnal fluctuations in O_3 concentration for all treatments between 8 May and 2 July 1982 are shown in Figure 4.2.2.2.

SO_2 was detected during over 50% of the hours between 8 May - 10 July, but the concentration was always considerably below the NAAQS. The highest 24-h mean, 3-h mean, 1-h mean, and instantaneous values were 0.018 ppm, 0.059 ppm, 0.085 ppm, and 0.210 ppm, respectively. The 24-h average, high 3-h average, and high 1-h daily means are presented in Figure 4.2.2.3.

Foliar injury and yield effects. Chlorosis was noted on some plants in all O_3 addition treatments on 19 May (after 11 exposure days) when the wheat began to head. Flowering began on 28 May, and most plants in all NF treatments exhibited some chlorosis. Necrotic tissue was noted on many plants in the NF + 0.06 and NF + 0.09 treatments at that time.

The ANOVA test indicated significant treatment effects for yield (kg/ha), seed wt/head, and 100-seed wt for all cultivars (Table 4.2.2.3). There were differences in the number of heads/meter (significant for the cultivar 'Abe') that did not appear related to treatment (Table 4.2.2.4), so an analysis of covariance was performed for kg/ha yield using number of heads/meter as the covariate. This analysis (adjusted kg/ha) also indicated significant treatment effects for each cultivar. There were no significant plot differences in plant height, plants/meter, or in any of the soil parameters tested. The treatment means for each plant variable measured are shown in Table 4.2.2.4. The grain yield of all three cultivars exhibited a consistent decrease as O_3 concentration increased. The yield reductions for 'Abe' and 'Arthur-71' were very similar for all yield parameters, with the losses caused primarily by reductions in seed size (39% and 39% at NF + 0.09) and some reductions in seed number (10% and 15% at NF + 0.09), respectively. The total yield reduction at NF + 0.09 for 'Roland' (63% in adjusted kg/ha) was greater than for 'Abe' and 'Arthur-71' (49% and 48%, respectively), with the losses caused by reductions in both seed size (50%) and seed number (25%). The differences between the AA and NF treatments were not significant for yield adjusted with the covariate analysis (adjusted kg/ha), 100-seed wt, or seed wt/head).

The parameters for the linear and Weibull regressions are shown in Table 4.2.2.3. A comparison of the R^2 values shows that the Weibull models provide only slight improvement over the linear models in this case. The Weibull regressions for adjusted kg/ha, seed wt/head, and 100-seed wt are displayed in

TABLE 4.2.2.2. HOURLY MEAN O_3 CONCENTRATIONS THAT WERE EXCEEDED FOR VARIOUS PERCENTAGES OF TIME DURING WHEAT EXPOSURE (MAY 8 - JULY 2, 1982) AT ARGONNE, ILLINOIS.

Timeframe	Treatment	# of Meas.	Min.	Percent of Time Concentration was Exceeded							Max.
				90	70	50	30	10	5	1	
0000-2400	AA-6 m*	1344	0.000	0.002	0.015	0.025	0.038	0.056	0.064	0.076	0.120
0900-1600	AA-6 m	392	0.001	0.020	0.033	0.041	0.053	0.066	0.073	0.081	0.120
0900-1600	AA**	392	0.000	0.018	0.032	0.040	0.050	0.063	0.068	0.080	0.113
0900-1600	CF	392	0.000	0.010	0.017	0.022	0.028	0.038	0.042	0.050	0.082
0900-1600	NF	392	0.000	0.019	0.031	0.040	0.049	0.064	0.071	0.080	0.120
0900-1600	NF + 0.03	392	0.000	0.037	0.058	0.069	0.080	0.097	0.103	0.117	0.149
0900-1600	NF + 0.06	392	0.000	0.055	0.085	0.098	0.111	0.129	0.136	0.156	0.170
0900-1600	NF + 0.09	392	0.000	0.073	0.112	0.128	0.142	0.163	0.173	0.191	0.220

* Ambient sampling point approximately 6 meters above ground, continuous monitoring.

** Ambient sampling point in field at top of canopy. Each hourly value for this and all chamber treatments was developed from three (occasionally two) two-minute samples per hour and averaged over four replicates.

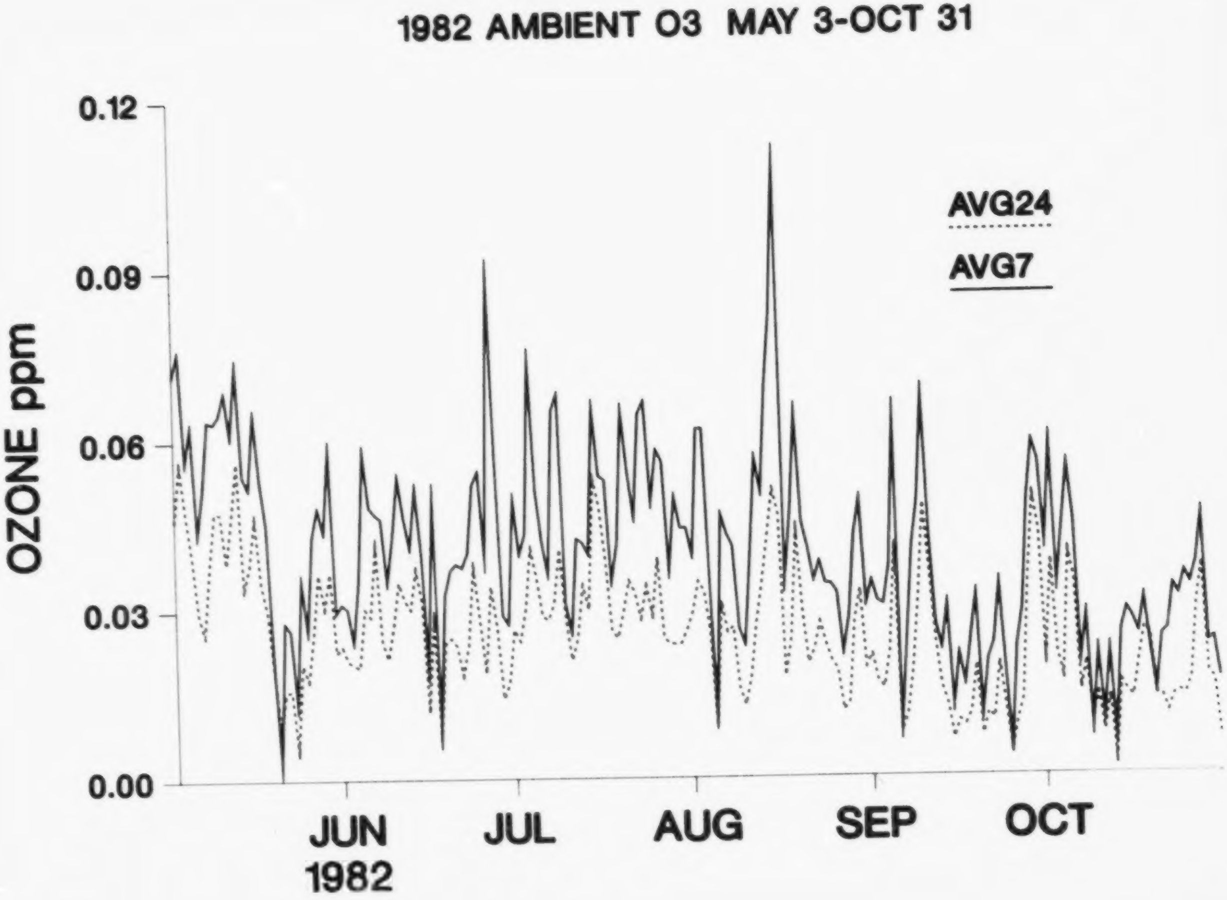

Figure 4.2.2.1. Ambient 7-h/day (average 7) and 24-h/day (average 24) O_3 data collected between 8 May and 31 October 1982 at Argonne, Illinois. Experimental treatment period was 8 May - 2 July.

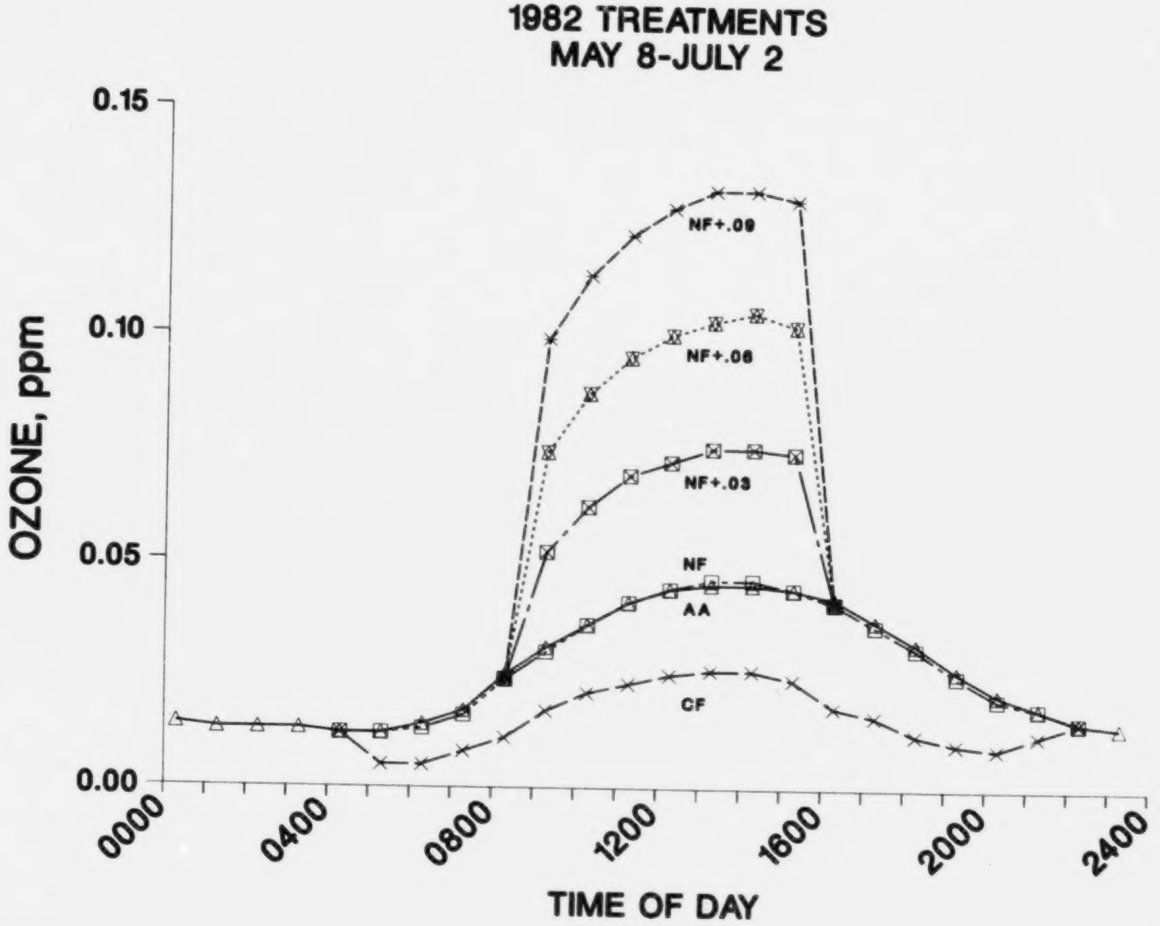

Figure 4.2.2.2. Mean diurnal changes in O_3 concentrations in ambient air (AA), charcoal-filtered air (CF), or in nonfiltered chambers (NF) with various amounts of O_3 added for 7-h/day (0900-1600 CST) during the exposure period at Argonne, Illinois. All chamber fans were turned off nightly from 2130-0530 CST.

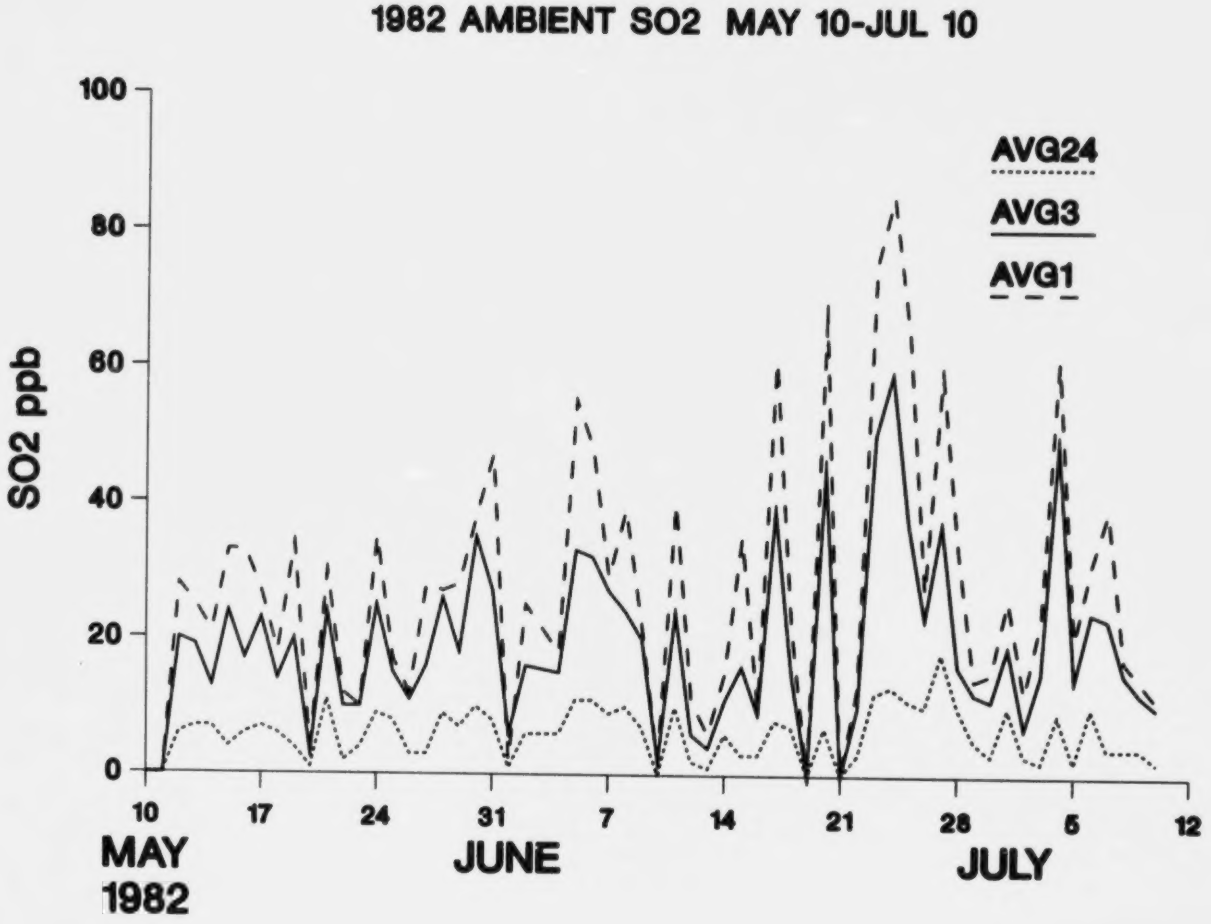

Figure 4.2.2.3. Ambient 24-h mean (average 24), 3-h peak mean (average 3), and 1-h peak mean (average 1) sulfur dioxide concentrations between 10 May and 10 July 1982 at Argonne, Illinois (1 ppm = 1000 ppb).

TABLE 4.2.2.3. MEAN SQUARES FROM ANOVA TEST TO DETERMINE SIGNIFICANCE OF TREATMENT EFFECTS AND REGRESSION ANALYSES OF DATA RESULTING FROM EXPOSURE OF THREE CULTIVARS OF WINTER WHEAT TO O_3 OCONCENTRATIONS OF 0.023, 0.041, 0.095 AND 0.122 FROM MAY 8 - JULY 2, 1982, AT ARGONNE, ILLINOIS.

			Abe				Arthur-71				Roland			
	Source	df	kg/ha	Adj. kg/ha†	Seed Wt./head	100-seed wt	kg/ha	Adj. kg/ha†	Seed Wt./head	100-seed wt	kg/ha	Adj. kg/ha†	Seed Wt./Head	100-seed wt
	Rep	3	1,412,599	169,055	0.0098	0.007	135,389	144,995	0.0237	0.0297	11,726	139,137	0.0130	0.074
	Treat	4	3,619,829*	4,990,533**	0.5966†	2,335*	2,786,031*	3,203,321**	0.6167**	2,066**	7,625,148**	6,946,512**	1.4232**	2,408**
	# Head	1	---	8,484,732**	---	---	---	7,208,249**	---	---	---	5,066,235†	---	---
	Error	12(11)	891,510	(201,218)	0.0944	0.044	656,820	(61,234)	0.0510	0.049	590,001	(183,070)	0.0650	0.051
Linear	Intercept		5,698.1	6,194.4	1.1136	4.94	5090.1	5214.3	1.1306	4.90	5933.8	5811.2	1.2991	4.06
	B		-21,469.9	-28,579.8	-4.77	-18.75	-20.359.5	-22,138.3	-4.85	-17.54	-34,435.9	-32,678.6	-7.41	-19.20
	R^2‡		0.814	0.923	0.976	0.962	0.950	0.968	0.977	0.953	0.944	0.965	0.986	0.979
Weibull	alpha		5,455.7	5339.7	0.9939	4.465	4488.6	4590.5	1.0065	4.395	5330.8	5450.7	1.2270	4.169
	sig		0.1778	0.1432	0.1471	0.1605	0.1486	0.1472	0.1468	0.1607	0.1146	0.1126	0.1142	0.1393
	c		1,452	2.455	2.130	2.101	2.509	2.339	2.1529	2.405	1.844	1.690	1.5695	1.148
	beta		---	69.193	---	---	---	49.142	---	---	---	69.667	---	---
	R^2		0.816	---§	0.995	0.988	0.998	---§	0.994	0.994	0.993	---§	0.990	0.990

* Significant at P = 0.05.

** Significant at P = 0.01.

† Adjusted by analysis of covariance with number of heads as covariate.

‡ R^2 = the amount of the treatment sum of squares from the ANOVA (or ANOCoVA) accounted for by the model.

§ R^2 calculation is difficult if not impossible because analysis of covariance and the Weibull regression adjust for the covariate differently.

TABLE 4.2.2.4. YIELD RESPONSE OF 3 CULTIVARS OF WINTER WHEAT EXPOSED TO CHARCOAL-FILTERED AIR (CF), AMBIENT AIR OPEN PLOT (AA), AND AMBIENT AIR PLUS O_3 DURING 1982 AT ARGONNE, ILLINOIS.*

Cultivar	Treatment	O_3† (ppm)	kg/ha	Adj.** kg/ha	100-seed wt (g)	Seed Wt/ Head (g)	Seed Wt/ Plant (g)	# Heads/ meter	# Seeds/ Head
Abe	AA	0.041	6202	5811	4.25	1.06	3.68	103.9	24.9
	CF	0.023	4926	5315	4.29	0.97	2.91	90.6	22.6
	NF	0.041	5343	5050	4.36	0.94	2.69	100.8	21.6
	NF + 0.03	0.068	4211	4633	3.80	0.84	2.53	89.3	22.1
	NF + 0.06	0.095	3174	3606	3.10	0.64	1.93	87.4	20.7
	NF + 0.09	0.122	3344	2736	2.60	0.53	1.85	113.5	20.4
Arthur-71	AA	0.041	5398	4746	4.23	0.95	3.30	100.8	22.5
	CF	0.023	4358	4647	4.32	1.00	3.11	78.4	23.2
	NF	0.041	4481	4300	4.26	0.92	3.03	86.8	21.6
	NF + 0.03	0.068	3768	3958	3.94	0.86	2.52	78.4	21.8
	NF + 0.06	0.095	3295	3151	3.24	0.67	1.97	86.9	20.7
	NF + 0.09	0.122	2443	2412	2.65	0.52	1.69	84.1	19.6
Roland	AA	0.041	6620	5771	3.56	1.15	4.25	102.6	32.3
	CF	0.023	5159	5007	3.64	1.12	3.34	82.3	30.8
	NF	0.041	4405	4668	3.32	1.03	2.92	75.4	31.0
	NF + 0.03	0.068	3744	3557	2.73	0.79	2.17	84.0	28.9
	NF + 0.06	0.095	2655	2455	2.07	0.55	1.75	85.9	26.6
	NF + 0.09	0.122	1687	1859	1.83	0.42	1.33	72.0	22.9

* Each value is the average of 4 replicates. Weight values are for 14% moisture content.

** Adj. kg/ha is kg/ha adjusted using # heads as the covariate (within cultivar).

† Seasonal 7 h/day mean.

Figures 4.2.2.4, 4.2.2.5, and 4.2.2.6. The adjusted kg/ha yield reductions predicted from the Weibull equation are 10%, 10%, and 24% at 0.06 ppm, and 33%, 32%, and 53% at 0.10 ppm (based on the 0.023 control treatment) for 'Abe,' 'Arthur-71,' and 'Roland,' respectively (Figure 4.2.2.4). The regressions for 100-seed wt (Figure 4.2.2.5) show that the apparent greater O_3 sensitivity of 'Roland,' as evidenced by the steeper slopes in the adj. kg/ha (Figure 4.2.2.4) and seed wt/head (Figure 4.2.2.6) regressions, is due primarily to effects on seed number rather than seed size.

Based on the only previous study with soft red winter wheats (four different cultivars than those used in this study) (Heagle et al., 1979), Weibull regressions predict losses of 3.6% (range 0.8-9.2) at 0.06 ppm O_3 and 17% (range 10.5-26.7) at 0.10 ppm O_3 based on a 0.025 ppm control (Heck et al., 1983). Our loss estimates average 14.6% (range 10-24) at 0.06 ppm and 39.3% (range 32-53) at 0.10 ppm. The study described in Section 4.2.1 reports even greater losses in a hard red winter wheat (53% at 0.06 ppm and 72% at 0.10 ppm).

Regressing yield against the other characterizations of O_3 exposure gives similar curves skewed to the right as the characterization goes from seasonal 7-h average, peak daily hourly concentration averaged over the season, highest 7-h average, and the highest seasonal hourly value (Figure 4.2.2.7). The same regressions were performed with the other crops studied since 1980 at CSRCLAP (Figure 4.2.2.8). These plots demonstrate that the loss estimates will be very similar irrespective of which of the four exposure estimates are utilized.

4.2.2.4 Conclusion

These results indicate that winter wheat may be somewhat more sensitive to O_3 than previously estimated by Heck et al. (1982a), although the most sensitive cultivar in this study ('Roland') is considerably less widely planted than the other two. The predicted yield reductions from 'Corsoy' soybean (17% at 0.06 and 42% at 0.10 ppm) rank this cultivar of soybean as more sensitive than 'Abe' and 'Arthur-71' but less sensitive than 'Roland.' All three wheat cultivars are more sensitive to O_3 than field corn or sorghum.

4.2.3 Impact of O_3 on Kidney Bean Photosynthesis, Growth, and Yield (NERCLAP)*

4.2.3.1 Introduction

The studies conducted with red kidney bean were designed to evaluate the effects of O_3 on photosynthesis, growth, and yield. The close relationship of these three elements within a plant suggests that their collective assessment may help provide a clearer understanding of the effects of O_3 on crop productivity. In an effort to pursue these integrated studies, the NCLAN dose-response research was complemented by physiological and growth studies which were funded by Boyce Thompson Institute.

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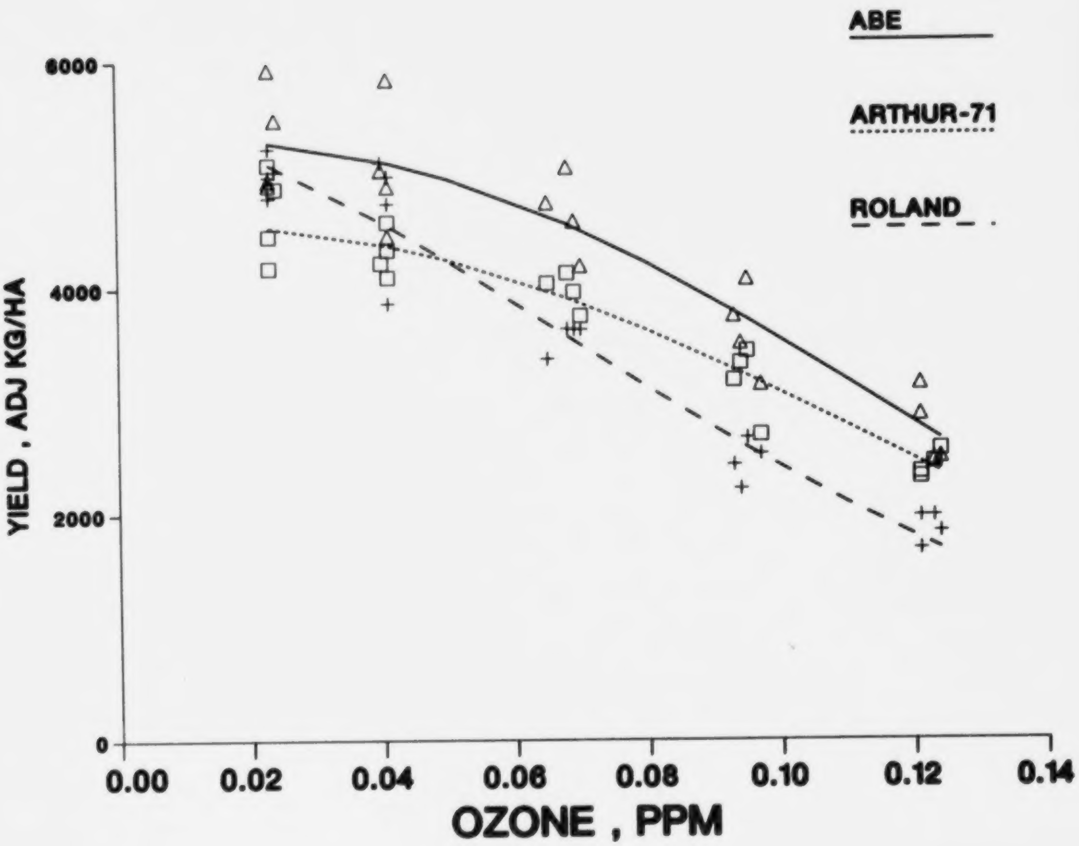
* Robert Kohut and Robert Amundson, Boyce Thompson Institute.

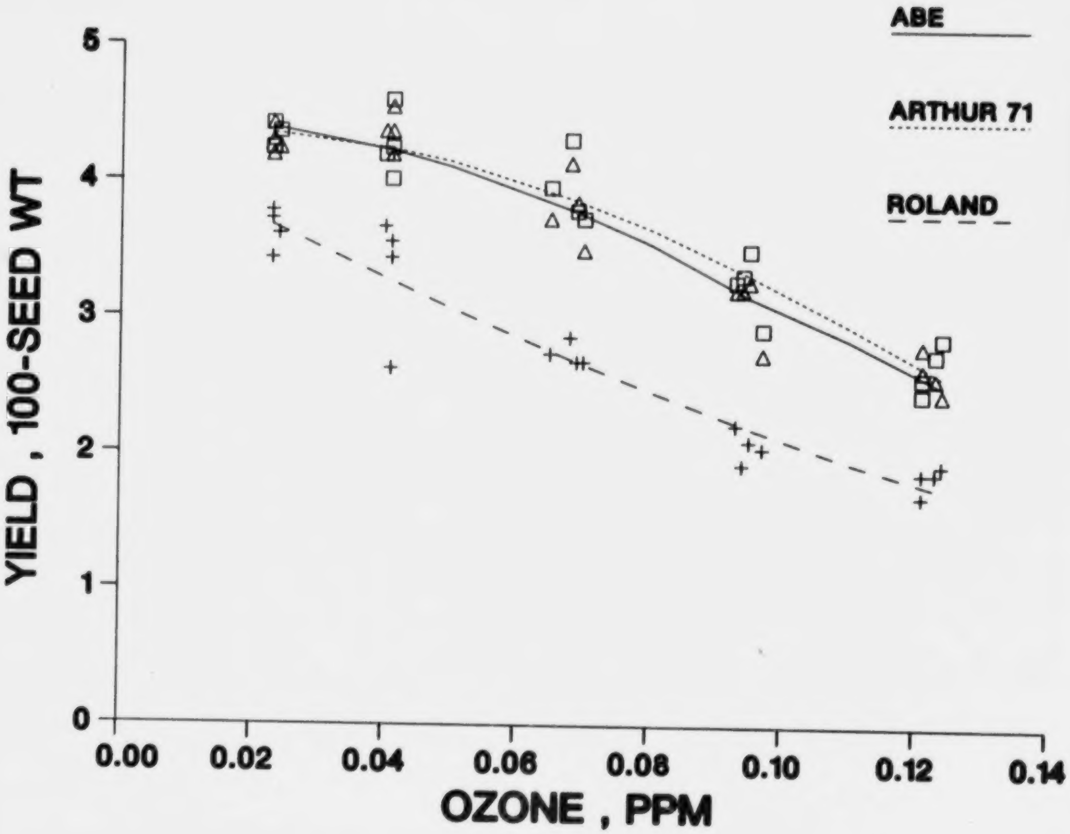


'Abe' $$Y = 5339.7\ e^{-\left(\frac{O_3}{.1432}\right)^{2.455}}$$

'Arthur-71' $$Y = 4590.5\ e^{-\left(\frac{O_3}{.1472}\right)^{2.3399}}$$

'Roland' $$Y = 5450.7\ e^{-\left(\frac{O_3}{.1126}\right)^{1.69}}$$

Figure 4.2.2.4. Weibull exposure-response equations for seed yield adjusted kg/ha 3 cultivars of winter wheat as a function of the seasonal 7-h daily average O_3 concentration at Argonne, Illinois.

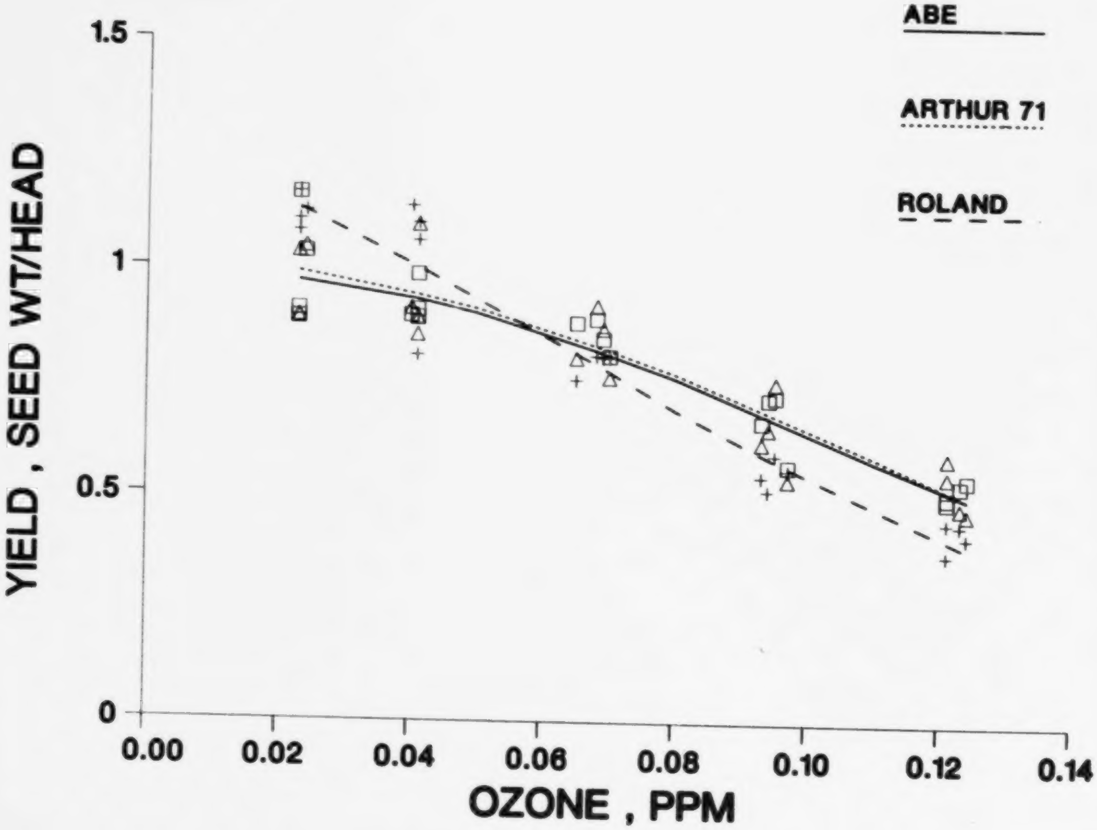


'Abe' $$Y = 4.465\, e^{-\left(\frac{O_3}{.1605}\right)^{2.101}}$$

'Arthur-71' $$Y = 4.395\, e^{-\left(\frac{O_3}{.1607}\right)^{2.405}}$$

'Roland' $$Y = 4.169\, e^{-\left(\frac{O_3}{.1393}\right)^{1.148}}$$

Figure 4.2.2.5. Weibull exposure-response equations for 100-seed wt of 3 cultivars of winter wheat as a function of the seasonal 7-h daily average O_3 concentration at Argonne, Illinois.



'Abe' $$Y = 0.9939\, e^{-\left(\frac{O_3}{.1471}\right)^{2.130}}$$

'Arthur-71' $$Y = 1.0065\, e^{-\left(\frac{O_3}{.1468}\right)^{2.1529}}$$

'Roland' $$Y = 1.227\, e^{-\left(\frac{O_3}{.1142}\right)^{1.5695}}$$

Figure 4.2.2.6. Weibull exposure-response equations for seed wt/head of 3 cultivars of winter wheat as a function of the seasonal 7-h daily average O_3 concentration at Argonne, Illinois.

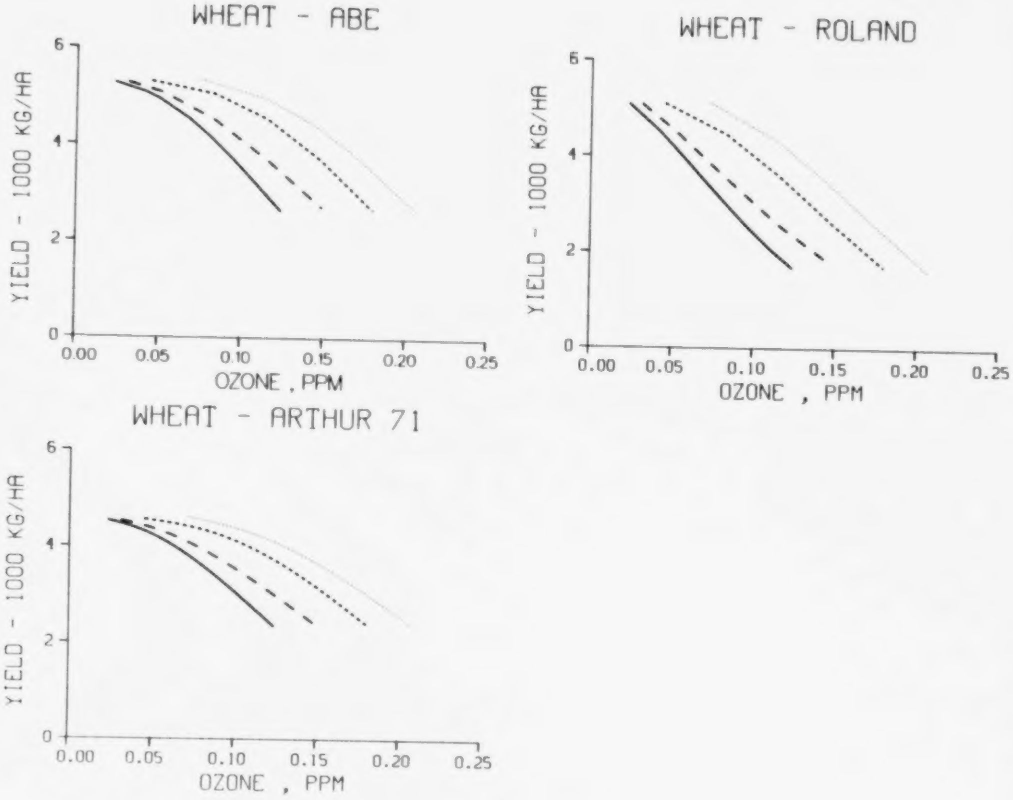


Figure 4.2.2.7. Exposure response curves (Weibull) for seed yield of winter wheat as a function of O_3 characterized as:

seasonal 7-h daily average (————————)
seasonal 1-h daily peak average) (- - - -)
single 7-h daily maximum (------------)
single 1-h maximum (·············)

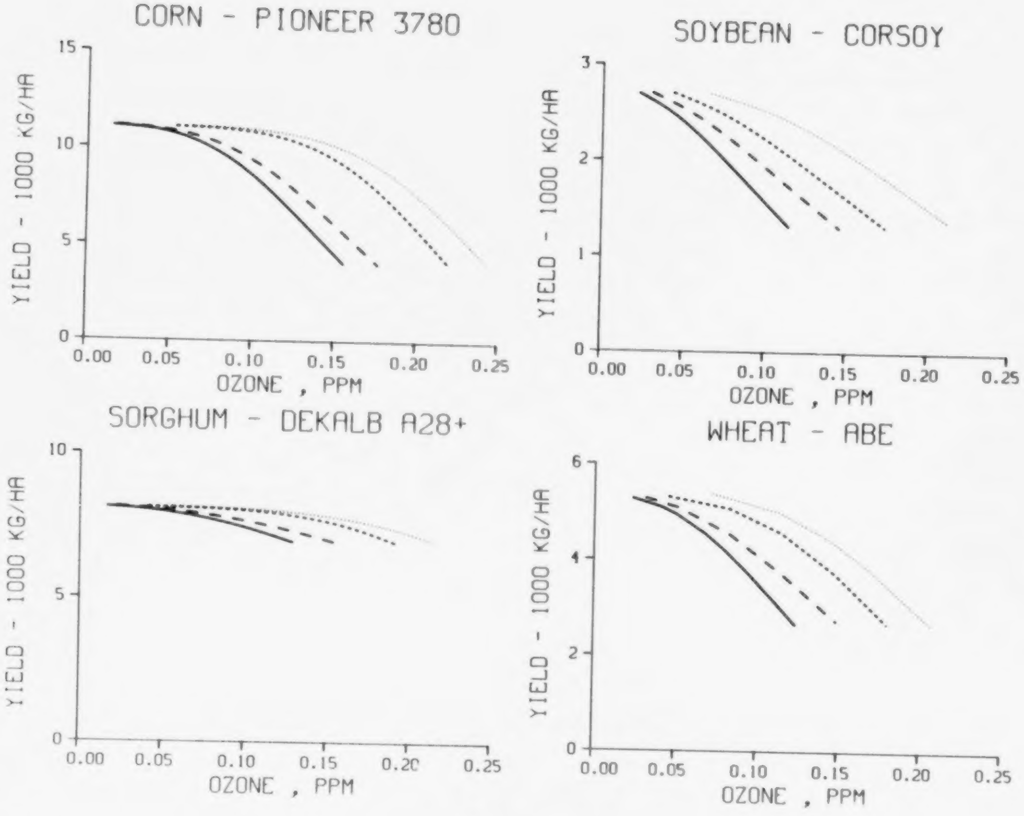


Figure 4.2.2.8. Exposure-response curves (Weibull) for seed yield of field corn, soybean, sorghum, and wheat as a function of O_3 characterized as:

seasonal 7-h daily average (_____________)
seasonal 1-h daily peak average) (- - - -)
single 7-h daily maximum (-------------)
single 1-h maximum (·············)

4.2.3.2 Materials and Methods

Cultural practices. Red kidney bean seed (*Phaseolus vulgaris* cv. California Light Red) was treated with *Rhizobium* inoculum and Protector II, an insecticide/fungicide seed protectant, and planted on June 24. Row spacing was 75 cm with a seed interval of approximately 5 cm. An application of 6-24-24 (NPK) fertilizer was banded at a rate of 196 kg/ha. The site had been treated with the herbicide Treflan 3 weeks prior to planting. After seedling emergence, hand weeding was conducted as necessary. Stand density was 16 to 18 plants per meter-row. Other than seed treatment, no pesticides were applied throughout the study. Plants were harvested on October 12.

Soil moisture at a depth of 25 cm was monitored with tensiometers. When tensiometer readings exceeded 70% of scale and leaf porometry measurements indicated midday stomatal closure, all experimental plots were hand irrigated. Irrigation was conducted on September 1 and September 13. Approximately 2.5 cm of water was applied to each plot during irrigation. The July through September experimental period received 8.57 cm of precipitation which was 1.88 cm below the 20-year average.

Pollutant treatments and monitoring. The O_3 generation, distribution, and monitoring systems were similar to those used in previous NCLAN studies (Kohut *et al*., 1981) and were based on those developed by Heagle *et al*. (1979). The five O_3 treatments in open-top chambers were charcoal-filtered air (CF), nonfiltered air (NF), and nonfiltered air to which either 0.03, 0.06, or 0.09 ppm O_3 was added (designated NF + 0.03, NF + 0.06, and NF + 0.09, respectively). Ambient air plots (AA) not enclosed by chambers comprised the sixth treatment. All chambers were in place and fans operating by August 3. Exposures were initiated on August 11 and terminated on October 6. The necessity of moving the chambers from the winter wheat study onto the red kidney beans prevented earlier exposures. Exposures were conducted daily except when precluded by rain or technical difficulties. Daily treatment periods were 7 h in duration from 1000 to 1700 EDT. Chamber fans were not operated between 2300 and 0500 to facilitate dew formation within the chambers.

O_3 monitoring was conducted with Monitor Labs Model 8410 O_3 monitors. Pollutant monitoring for each chamber was on a timesharing basis using an automated sequencing system. The line loss for each O_3 sampling line was determined three times during the study. These losses were taken into account in establishing the chamber pollutant levels and later during the reduction of the O_3 monitoring data. All O_3 monitors used in the study were subject to the NCLAN quality assurance program.

Chambers. The field experiment employed two types of open-top chambers (Heagle *et al*., 1973; Mandl *et al*., 1973) and consisted of two separate but integrated studies. The two field studies complemented each other; one investigated the effects of the O_3 treatments on photosynthesis and plant growth while the other assessed the relationship between O_3 and final crop yield. Figure 4.2.3.1 depicts the O_3 treatments and allocation of chamber types in the two studies. A randomized complete block design of six replications of six treatments was used. The locations of the 36 experimental plots were established after the stand had developed to the point that it could be evaluated for uniform density and growth.

TREATMENT	DOSE-RESPONSE		PHYSIOLOGY and GROWTH CURVES			
			Aug	Sept/Oct	Aug	Sept/Oct
Ambient	●	●	●	●	●	●
Charcoal-filtered	○	○	○	○	◒	◒
Nonfiltered	○	○	○	○	◒	◒
Nonfiltered +.03	○	○	○	○	◒	◒
Nonfiltered +.06	○	○	○	○	◒	◒
Nonfiltered +.09	○	○	○	○	◒	◒

Chamberless plot ● BTI-type chamber ◒

EPA-type chamber ○

Figure 4.2.3.1. Allocation of open-top chambers among experiments and treatments in the red kidney bean study at Ithaca, New York, in 1982. This figure does not represent the spatial arrangement of the chambers.

Physiology. Net photosynthesis was monitored by enclosing the center leaflet of a red kidney bean leaf in a transparent cuvette and measuring the decrease in CO_2 concentration within the cuvette over a known time interval (Ehleringer and Cook, 1980). Measurements of CO_2 concentrations were made as described in the 1981 NCLAN annual report (Kohut and Amundson, 1982). Initially, leaflets to be sampled were tagged for identification and the outline traced to measure surface area. For each sampling interval, the net photosynthetic rates of the leaflets in each treatment were monitored. The net photosynthetic rate of each leaflet was determined twice within a 3 to 5 minute period. Therefore, the time taken to sample 2 leaflets in each treatment was approximately 10 minutes. Stomatal conductances were monitored on the same leaflets immediately after the net photosynthesis measurements and on additional leaflets at other times with a steady state porometer (LICOR, Model 1600).

Growth Analysis. Plants were harvested on 12 separate dates through the growing season to quantify the rate of red kidney bean growth and development in each experimental treatment. The first six harvests were made before O_3 additions began. For the final six harvests, starting on August 18, plants were sampled from both the ambient and chamber plots.

When obtaining a sample for growth analysis, all plants in two 0.5 m sections in two adjacent rows near the center of the chamber were cut. When a chamber was sampled for the second and third times, approximately three to five plants in each row nearest the last sample were considered buffer plants and were discarded. This was done to minimize any potential edge effects resulting from reduced competition for light, water, and nutrients, and from the possible increased infiltration of O_3 into the plant canopy. Replicate samples from two chambers for each O_3 treatment were collected on each sampling date.

Dose-Response. The dose-response study employed a replicated design. Two replicates contained plants that were undisturbed until harvest and two replicates contained plants that remained after sampling for the growth study. All replicates were harvested on October 12. Plants were harvested from four 0.5 m row sections in the center of the undisturbed chambers and from two 0.5 m row sections in the center of the growth study chambers. Numbers of pods, pod dry weight, seed dry weight, and number of seeds were evaluated. Weights were obtained after drying at 65°C for 48 h; at that time the moisture content of the seed was approximately 10%. Harvest data were obtained in accordance with the NCLAN biological quality assurance program.

Harvest data were evaluated using analysis of variance. Dose-response relationships for yield were assessed with regression analysis techniques.

4.2.3.3 Results

Pollutant Treatments and Monitoring. Ambient air monitoring was conducted for 83 days during the experiment from July 22 through October 12. Exposures were conducted between August 11 and October 6. These periods were designated the monitoring and exposure periods, respectively. During the exposure period, O_3 additions were conducted on 43 days and there were 14 days on which there were no additions due to weather or technical problems.

The highest 1-h ambient O_3 concentration recorded during the monitoring period was 0.086 ppm with a second highest concentration of 0.083 ppm. The average daily 1-h maximum concentration was 0.047 ppm. The 1-h average concentration of 0.08 ppm was exceeded 9 times during the monitoring period.

The 7-h and 24-h average O_3 concentrations for the monitoring and exposure periods are presented in Table 4.2.3.1. Charcoal filtration reduced the O_3 level to approximately 50 to 60% of ambient. The increments in the O_3-added treatments were somewhat below the target values but provided distinct treatment levels and a range of concentrations. The highest and second highest 1-h concentrations, the average daily 1-h maximum, and the maximum 7-h concentration for each treatment are presented in Table 4.2.3.2. The number of instances in which the 1-h O_3 concentrations of 0.08 and 0.12 ppm were exceeded in each treatment are presented in Table 4.2.3.3.

Physiology. Net photosynthetic rates of individual leaflets were measured on 4 days before and after the O_3 treatments started. No effects of O_3 on net photosynthesis of kidney bean were detected. The rates of net photosynthesis ranged between 5 and 40 mg CO_2 dm^{-2} h^{-1} with most values between 25 and 30 mg CO_2 dm^{-2} h^{-1}. Unfortunately, the rates measured within a 10 min period on the same leaflet varied as much as did the rates within or between treatments. Possible reasons for the high variability in these measurements are considered in the discussion section that follows.

The chambers were positioned in the field and the chamber blowers were activated on 3 August, but the O_3 exposures were not started until 11 August. During this pre-exposure period, stomatal conductances were monitored in plants within 10 chambers that would receive the O_3 treatments. Stomatal conductances ranged from 0.6 to 2.5 s cm^{-1}, but they did not differ among the chambers. After the exposures began, stomatal conductances were monitored on 10 days from 11 August until 5 September. The average conductances for that period are presented in Figure 4.2.3.2. Within the chambers, average stomatal conductances decreased as O_3 concentrations increased. For example, stomatal conductances in the charcoal-filtered treatments (CF) averaged 1.42 cm s^{-1} while stomatal conductances of plants exposed to the highest concentrations of O_3 (NF + 0.09) averaged 0.67 cm s^{-1}. Plants exposed to ambient concentrations of O_3 had the highest stomatal conductances (1.58 cm s^{-1}).

Growth Analysis. The effects of the treatments on the aboveground dry mass of red kidney bean are shown in Figure 4.2.3.3. There was a high degree of variability in values at the first destructive harvest on 18 August but by early September the plants exposed to the higher O_3 concentrations had lower aboveground biomass. Changes in pod dry weight were also monitored and are shown in Figure 4.2.3.4. As was found for the aboveground biomass, there were no distinct trends in treatment effects on pod dry weight until early September, when the higher concentrations of O_3 were found to reduce pod dry weights.

Dose-response. O_3 injury, in the form of foliar stipple and premature senescence, appeared first and developed to the greatest degree at the highest O_3 treatment level. As the level of O_3 decreased, the incidence of injury declined. No symptoms of O_3 injury were evident in the charcoal-filtered, ambient, and nonfiltered air treatments. A very light incidence of powdery mildew (most likely *Erysiphe polygoni*) was found in all experimental plots.

TABLE 4.2.3.1. AVERAGE O_3 CONCENTRATIONS (ppm) FOR EACH TREATMENT IN THE RED KIDNEY BEAN STUDY AT ITHACA, NEW YORK, IN 1982.

Treatment	Monitoring Period* 7-h	Monitoring Period* 24-h	Exposure Period** 7-h	Exposure Period** 24-h
CF	0.023	0.017	0.019	0.014
AA	0.037	0.027	0.036	0.026
NF	0.040	0.028	0.040	0.027
NF + 0.03	0.054	0.032	0.069	0.033
NF + 0.06	0.073	0.038	0.089	0.042
NF + 0.09	0.087	0.042	0.109	0.047

* The monitoring period was from July 22 through October 12.

** The exposure period was from August 11 through October 6.

TABLE 4.2.3.2. HIGHEST AND SECOND HIGHEST 1-H AVERAGE, THE AVERAGE DAILY 1-H MAXIMUM, AND THE MAXIMUM 7-H AVERAGE O_3 CONCENTRATIONS (ppm) FOR EACH TREATMENT DURING THE MONITORING PERIOD IN THE RED KIDNEY BEAN STUDY AT ITHACA, NEW YORK, IN 1982.

Treatment	Max. 1-h	Second Max. 1-h	Average Daily 1-h Max.	Max. 7-h
CF	0.072	0.069	0.034	0.060
AA	0.086	0.083	0.047	0.074
NF	0.092	0.084	0.049	0.083
NF + 0.03	0.126	0.123	0.067	0.113
NF + 0.06	0.174	0.164	0.093	0.160
NF + 0.09	0.214	0.195	0.111	0.188

TABLE 4.2.3.3. NUMBER OF OCCASIONS ON WHICH THE 0.08 AND 0.12 ppm 1-H O_3 CONCENTRATIONS WERE EXCEEDED IN THE RED KIDNEY BEAN STUDY AT ITHACA, NEW YORK, IN 1982.

Treatment	Monitoring Period* 0.08	Monitoring Period* 0.12	Exposure Period** 0.08	Exposure Period** 0.12
CF	1	0	9	0
AA	9	0	8	0
NF	18	0	17	0
NF + 0.03	91	4	90	4
NF + 0.06	264	92	263	92
NF + 0.09	292	214	291	214

* The monitoring period was from July 22 through October 12.

** The exposure period was from August 11 through October 6.

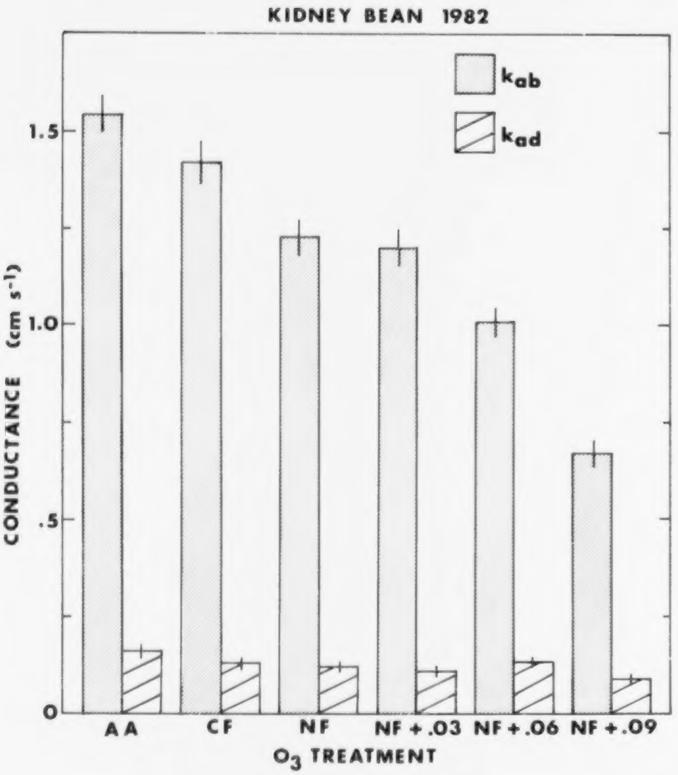


Figure 4.2.3.2. Effect of O_3 on conductance of abaxial (k_{ab}) and adaxial (k_{ad}) leaf surfaces of kidney bean exposed to different O_3 concentrations at Ithaca, New York.

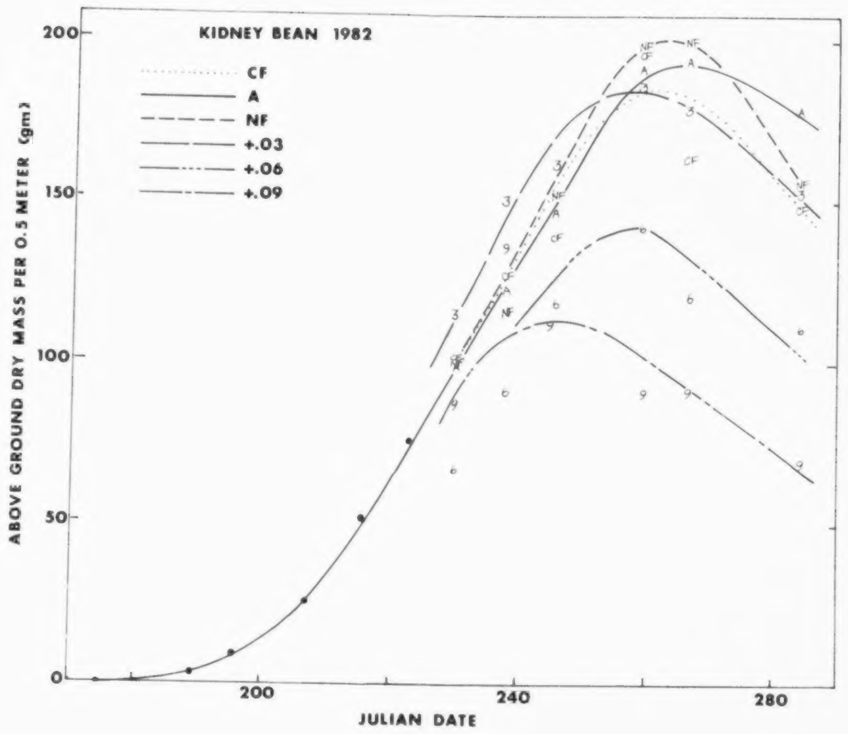


Figure 4.2.3.3. Effect of O_3 on aboveground biomass of kidney bean at Ithaca, New York.

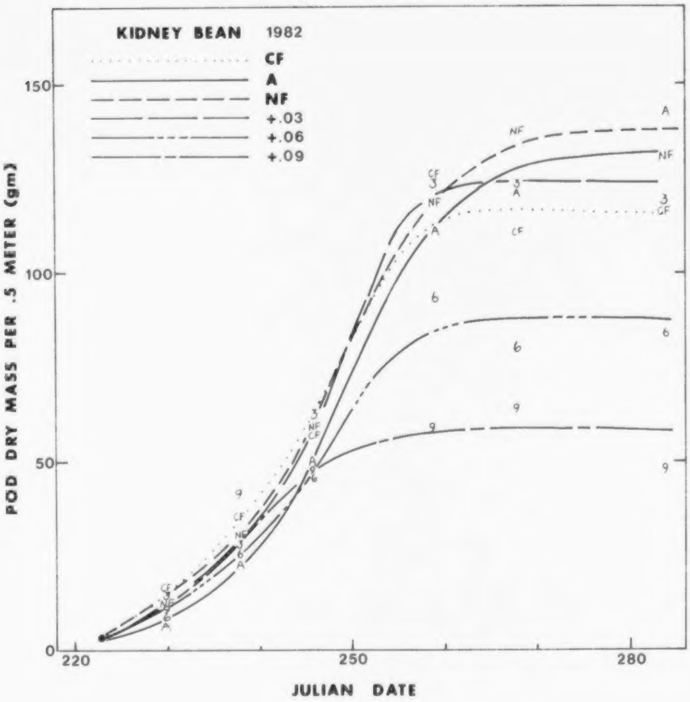


Figure 4.2.3.4. Effect of O_3 on pod dry mass of kidney beans at Ithaca, New York.

Harvest data are presented in Table 4.2.3.4. Compared to the yield in the charcoal-filtered treatment, there were yield increases in the ambient and nofiltered air treatments. All O_3-added treatments showed yield reductions. Results of the analysis of variance for the yield data are in Table 4.2.3.5. Significant treatment effects were found for all yield variables. No differences were found between the data obtained from the undisturbed chambers (full) and the growth analysis chambers (partial).

Regression analysis was conducted using data from all open-top chamber treatments. Data from the full and partial plots were used together for the linear regression analysis since the analysis of variance indicated that they were not significantly different. The Weibull analysis was used to evaluate the full and partial plots separately and to test whether a combined model could be accepted. Regression analyses were conducted for both the monitoring and exposure periods. The dose-response functions are presented in Table 4.2.3.6. Regression analysis using the Weibull model for the 7-h O_3 concentrations during the monitoring period indicated that the combined model could be accepted for the full and partial plots. The combined model was rejected for the exposure period.

4.2.3.4 Discussion

Exposure to O_3 produced significant impacts on the yield of California Light Red kidney bean although the effects at the lower treatment levels were not consistent. Among the chamber treatments, yields in the charcoal-filtered and nonfiltered treatments were similar with major reductions being produced as O_3 was added. The yield reductions produced by the O_3-added treatments were considerably greater than those produced in the 1980 NCLAN study (Kohut *et al.*, 1981). The longer exposure period in the present study is probably the major factor responsible for the greater treatment effect.

Collection of photosynthesis data to augment the dose-response information was confounded by the high degree of variability in the readings taken on individual leaflets. Elevation of CO_2 within the open-top chambers was the main factor that contributed to the high variability of the net photosynthesis readings. Two people were required to make the measurements and depending on wind speed and direction it was difficult to keep the open-top chambers free from CO_2 contamination. Occasionally, samples had CO_2 concentrations as high as 450-500 ppm. Therefore, the depletion rate was enhanced by a net loss of CO_2 from the cuvette by diffusion and leakage and also by higher rates of CO_2 fixation due to higher intercellular CO_2 concentrations. A related factor that contributed to the variability was the relatively short time (30 sec) that the cuvette was kept on the leaflet. A longer depletion time (45-60 sec) would have produced greater CO_2 differentials and the CO_2 analysis error (± 2 ppm) would have been a smaller proportion of the measured CO_2 depletion. However, longer sample times would have also increased the risk of elevated CO_2 concentrations within the open-top chambers.

Although no effects of O_3 on net photosynthesis were detected (most likely due to technical problems previously discussed), O_3 significantly reduced stomatal conductances. Chronic exposures to low concentrations of O_3 have been shown to cause linear reductions in stomatal conductance and net photosynthesis of pine (Coyne and Bingham, 1981) and soybean (Reich *et al.*,

TABLE 4.2.3.4. RED KIDNEY BEAN HARVEST DATA FROM THE 1982 STUDY AT ITHACA, NEW YORK. TREATMENT MEANS ARE FROM THE COMBINED UNDISTURBED AND GROWTH ANALYSIS PLOTS.

Treatment	Pods (#/m-row)	Pod Weight (kg/ha)	Seeds (#/m-row)	Seed Weight (kg/ha)	Seed Weight % Change
CF	91	3211	312	2390	
AA	104	3646	347	2675	+12
NF	95	3230	325	2420	+ 1
NF + 0.03	87	2689	283	1979	-17
NF + 0.06	72	2026	227	1459	-38
NF + 0.09	59	1425	155	1015	-58

TABLE 4.2.3.5. ANALYSIS OF OPEN-TOP CHAMBER HARVEST DATA FOR RED KIDNEY BEAN FROM THE 1982 STUDY IN ITHACA, NEW YORK.

		Mean Squares			
Source of Variation	df	Pod Number	Pod Weight	Seed Number	Seed Weight
Block	3	352.0	341056	3866.1	161511
Treatment	4	865.0**	2455295**	19456.9**	1483247**
Full or Partial	1	655.5*	404100	4205.0	111281
Linear	1	2985.5**	29276408**	68859.3**	5598654**
Quadratic	1	435.7	416259	8120.9*	234039
Cubic	1	31.0	63323	120.2	55051
Treat x Block	12	128.7	158070	1697.4	82159

F values determined by the ratio of the block or treatment mean square to the treatment x block (error) mean square.

* PR (value > F critical) = 0.05.

** PR (value > F critical) = 0.01.

TABLE 4.2.3.6. LINEAR AND WEIBULL REGRESSION EQUATIONS FOR RED KIDNEY BEAN YIELD. O_3 CONCENTRATIONS ARE THE MONITORING PERIOD (MP) AND EXPOSURE PERIOD (EP) 7-H AVERAGE IN ppm. ALL YIELDS ARE kg/ha.

Linear

Yield = 3127.4 - 22997.3 (MP) $R^2 = 0.74$

Yield = 2887.0 - 16304.4 (EP) $R^2 = 0.76$

Weibull -- Analysis of Full and Partial Plots

A: Monitoring Period -- Accept Combined Model

$\text{Yield (full plot)} = 2477.8 \exp - (MP/0.0903)^{2.785}$

$\text{Yield (partial plot)} = 2634.2 \exp - (MP/0.0903)^{2.785}$

B: Exposure Period -- Reject Combined Model

$\text{Yield (full plot)} = 2871.9 \exp - (EP/0.113)^{1.298}$

$\text{Yield (partial plot)} = 2443.8 \exp - (EP/0.0108)^{3.935}$

1983). Rates of net photosynthesis and stomatal conductance are highly correlated (for a recent review see Farquhar and Sharkey, 1982), consequently it is difficult to believe that O_3 reduced stomatal conductances, but had no effect on net photosynthesis. Since the growth and yield of these plants were reduced by elevated concentrations of O_3, it would be consistent with the results of previous studies to assume that O_3 also reduced net photosynthesis.

4.2.3.5 Conclusions

Aboveground dry weight and pod dry weight were significantly reduced by the NF + 0.06 and NF + 0.09 treatments compared to the four lowest O_3 treatments after three weeks of exposure to O_3. However, over the same time period, trends for differences in growth and pod development among the four lowest O_3 treatments were not apparent. Changes in net photosynthetic rates were not detected for technical reasons, but stomatal conductances were linearly reduced with exposure to higher concentrations of O_3. At the final harvest, yield had a negative linear relationship to O_3 concentration with a 58 percent reduction in yield at the highest O_3 concentration (0.109 ppm) compared to the yield of plants exposed to charcoal-filtered air (0.019 ppm).

4.2.4 Impact of O_3 on Grain Sorghum (CSRCLAP)*

4.2.4.1 Introduction

Grain sorghum is the fifth most important crop in the United States in acreage planted (4%), and seventh in dollar value (5%). It is an important crop in some areas of the Midwest, primarily where the amounts of rainfall are too small for adequate field corn production. This study followed the previously described wheat study (Section 4.2.2) and had similar objectives. Specifically, the objective was to establish the exposure-response relationships between yield of sorghum and chronic exposures to a range of O_3 concentrations. No previous information regarding the sensitivity of sorghum to O_3 was available.

4.2.4.2 Materials and Methods

Grain sorghum (*Sorghum vulgare* Pers. DeKalb A28+) seeds were planted on 24 June 1982 in a portion of our field previously cropped in soybean (1980) and field corn (1981). This widely planted early maturing hybrid was selected based upon the recommendation of a DeKalb Ag Research, Inc., representative. The plot had been fertilized on 12 June with 672 kg/ha 9-23-30 and 435 kg/ha ammonium nitrate (33.5-0-0). The previous fall the plot had received 40 kg/ha N and 103 kg/ha P (18-46-0) and was planted to winter wheat, which was plowed down in May. The soil is a Morley silt loam, gray-brown podzolic, upland timber soil with a high water holding capacity, low permeability, a pH of 6.57 ± 0.36, and 9509 ± 1168 kg/ha organic matter. Hand planting was done on a 0.76 m row spacing with two seeds every 5 cm. Thinning to 1 plant/5 cm (20 plants/m or 43,000 plants/ha) was accomplished immediately prior to initiation of exposure treatments, when the plants were 7-10 cm tall. Open-top chambers were moved in place on 13 July and exposures began on 16 July. Minimal weed control was required and this was accomplished by hand. Supplemental irrigation was not required since above normal precipitation (31 cm) occurred between 27 June and 9 October.

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* Lance W. Kress and Joseph E. Miller, Argonne National Laboratory.

A randomized complete block design was used incorporating three blocks of six chamber treatments. The treatments were:

CF, charcoal-filtered air;

NF, non-filtered air chambers with a small amounts of O_3 added to provide a concentration equal to that in the AA plot;

and NF + 0.02, NF + 0.04, N + 0.07, and NF + 0.10 in which O_3 was added to NF chambers in sufficient amounts to approximate 0.02, 0.04, 0.07, and 0.10 ppm of O_3 above ambient, respectively.

There was one extra replicate of both the NF + 0.02 and NF + 0.04 treatments in one block. Exposures were ended on 8 October and the grain was harvested on 14 October. There were also 46 companion plots of two 1 m rows each located systematically throughout the field. The yields from the companion plots were intended to be used in an analysis of covariance. The mean yield of the four companion plots around each NF plot was used as the ambient air (AA) plot in the evaluation for possible chamber effects.

The methods for generating and monitoring O_3 have been described in Section 4.2.2. The adjustments for O_3 loss in chamber sampling lines varied from 3-10%. O_3 was not dispensed on three full and four half days due to rain. An independent audit of our monitoring instruments was performed on 7 September (as dictated by the NCLAN Quality Assurance Plan) and all instruments were certified to be in excellent or satisfactory operating condition.

Measurements taken at harvest were foliar injury on the four uppermost leaves, plant height, and number of plants per meter. Grain was hand threshed and cleaned, oven dried (to < 1% moisture), and weighed. Seed weight per meter of row (four one-meter rows per chamber plot were harvested) was adjusted to reflect 15.5% moisture content and converted to kilograms per hectare (kg/ha). The weight of 100 seeds (100-seed wt) was also obtained for each plot. The number of plants and heads was identical in each plot. Soil samples were sent to the Soil and Plant Analysis Laboratory, University of Wisconsin, for analysis of pH, organic matter, P, and K.

An analysis of variance was performed on the yield data using the general linear models (GLM) procedure of the Statistical Analysis System (SAS). Weibull and plateau-linear regressions were developed for all chamber treatments using the NLIN procedure of SAS.

4.2.4.3 Results and Discussion

Pollutant concentrations. The mean seasonal O_3 concentration (7-h/day mean) from 16 July to 8 October 1982 for the AA, CF, NF, NF + 0.02, NF + 0.04, NF + 0.07, and NF + 0.10 ppm treatments were 0.039, 0.016, 0.040, 0.059, 0.078 ppm, 0.102 ppm, and 0.129 ppm, respectively (Table 4.2.4.1). The ratio of the highest 7-h/day value to the seasonal 7-h/day mean ranged progressively from

TABLE 4.2.4.1. HIGHEST AND SECOND HIGHEST HOURLY O_3 (ppm), MEAN, THE HIGHEST 7-H MEAN, THE SEASONAL MEAN 1-H PEAKS, HIGHEST 7-H MEAN, AND THE SEASONAL 7-H MEANS FOR EACH TREATMENT AT ARGONNE, ILLINOIS, IN 1982.*

	7 h/day Values		1 h/day Peak Values		
Treatment	Seasonal Mean	Highest	Seasonal Mean	Highest	Second Highest
AA	0.039	0.107	0.049	0.124	0.120
CF	0.016	0.041	0.022	0.060	0.057
NF	0.040	0.098	0.051	0.120	0.106
NF + 0.02	0.059	0.122	0.072	0.145	0.144
NF + 0.04	0.078	0.143	0.095	0.175	0.169
NF + 0.07	0.102	0.167	0.123	0.198	0.196
NF + 0.10	0.129	0.191	0.143	0.223	0.220

* Each value was developed from three (occasionally two) two-minute samples per hour. The mean 1-h and 7-h values are averages of three replicates.

1.48 in the NF + 0.10 treatment to 2.74 in the AA treatment. The higher ratios for the low pollution treatments in this experiment compared to the wheat experiment (Chapter 4.2.2) are due to the seasonal O_3 variation in northern Illinois which produces consistently lower O_3 concentrations in September and October. The seasonal means of 1-h/day peak values were 21-26% above the seasonal 7-h/day means for all treatments except the CF and NF + 0.10 treatment which were 38% and 11% greater, respectively. The CF chambers were effective in excluding 55-60% of the ambient O_3.

The seasonal hourly average O_3 data are presented as concentrations that are exceeded for various percentages of the time during the exposure period (Table 4.2.4.2). The ambient O_3 concentrations at canopy level (AA) were generally about 5% lower than those measured six meters above ground (6 m). The NAAQS were < 1% of the hours in the NF + 0.02 treatment, approximately 5% of the hours in the NF + 0.04 treatment, somewhat less than 30% of the hours in the NF + 0.07 treatment, and approximately 70% of the hours in the NF + 0.10 treatment.

Daily 7- and 24-h mean O_3 concentrations are shown in Figure 4.2.2.1 (previous section). The mean seasonal diurnal fluctuations in O_3 concentration for the experimental treatments are presented in Figure 4.2.4.1.

SO_2 was detected during about 50% of the hours between 10 July - 8 October, but the concentration was always considerably below the NAAQS (Figure 4.2.4.2). The highest 24-h mean, 3-h mean, 1-h mean, and instantaneous peak values were 0.034 ppm, 0.122 ppm, 0.175 ppm, and 0.270 ppm, respectively.

Height, foliar injury, and yield effects. Plants were slightly taller in chambers compared to the open plots, but there were no significant O_3 treatment effects on plant height (Table 4.2.4.3). Foliar injury was increased at only the two highest O_3 treatments. Injury in the NF + 0.07 ppm treatment was characterized by increased chlorosis and necrosis, while injured leaves in the NF + 0.10 ppm treatment had increased stipple as well as necrosis (Table 4.2.4.3). Development of heads (17 August), initiation of flowering (24 August) and the rate of maturation appeared to be unaffected by the treatments except that leaf senescence was slightly enhanced (less than one week) in the two highest O_3 treatments.

The ANOVA indicated significant treatment effects for yield (kg/ha) and 100-seed wt (Table 4.2.4.4). The companion plot and soil analysis data indicated no significant differences among the plots, so no further use was made of them.

There was a chamber effect on the yield of sorghum (Table 4.2.4.5). Total yields were significantly greater but the seeds were significantly smaller in the AA plots compared to the NF chambers. For this reason, the AA plot data were not used in the exposure-response evaluations. Evaluating only the chamber treatments, there was a slight general decrease in yield as O_3 concentration increased. This decrease was due primarily to smaller seed size. The NF + 0.02 and NF + 0.04 treatment exhibited slightly greater yield than the NF treatment due to increased seed numbers. A similar slight stimulation in yield with increasing O_3 concentration was observed in 1981 with the field corn hybrid 'PAG 397' (Heck *et al.*, 1982b).

TABLE 4.2.4.2. HOURLY MEAN O_3 CONCENTRATIONS THAT WERE EXCEEDED FOR VARIOUS PERCENTAGES OF TIME DURING SORGHUM EXPOSURES (JULY 16 - OTOBER 8, 1982) AT ARGONNE, ILLINOIS.

Timeframe	Treatment	# of Meas.	Min.	Percent of Time Concentration is Exceeded							Max.
				90	70	50	30	10	5	1	
			O_3 (ppm)								
0000-2400	6 m*	2040	0.000	0.001	0.010	0.021	0.034	0.053	0.064	0.079	0.128
0900-1600	6 m	595	0.002	0.015	0.029	0.039	0.049	0.068	0.074	0.087	0.128
0900-1600	AA**	595	0.000	0.015	0.028	0.038	0.047	0.064	0.071	0.083	0.124
0900-1600	CF	595	0.000	0.005	0.009	0.013	0.019	0.031	0.038	0.047	0.060
0900-1600	NF	595	0.000	0.016	0.029	0.039	0.049	0.064	0.071	0.085	0.120
0900-1600	NF + 0.02	595	0.000	0.030	0.047	0.058	0.070	0.088	0.096	0.113	0.145
0900-1600	NF + 0.04	595	0.000	0.046	0.066	0.079	0.091	0.111	0.119	0.138	0.175
0900-1600	NF + 0.07	595	0.000	0.067	0.092	0.106	0.118	0.138	0.149	0.168	0.198
0900-1600	NF + 0.10	595	0.000	0.092	0.119	0.133	0.147	0.167	0.180	0.203	0.223

* Ambient sampling point approximately 6 meters above ground, continuous monitoring.

** Ambient sampling point in field at top of canopy. Each hourly value for this and all chamber treatments was developed from three (occasionally two) two-minute samples per hour and averaged over four replicates.

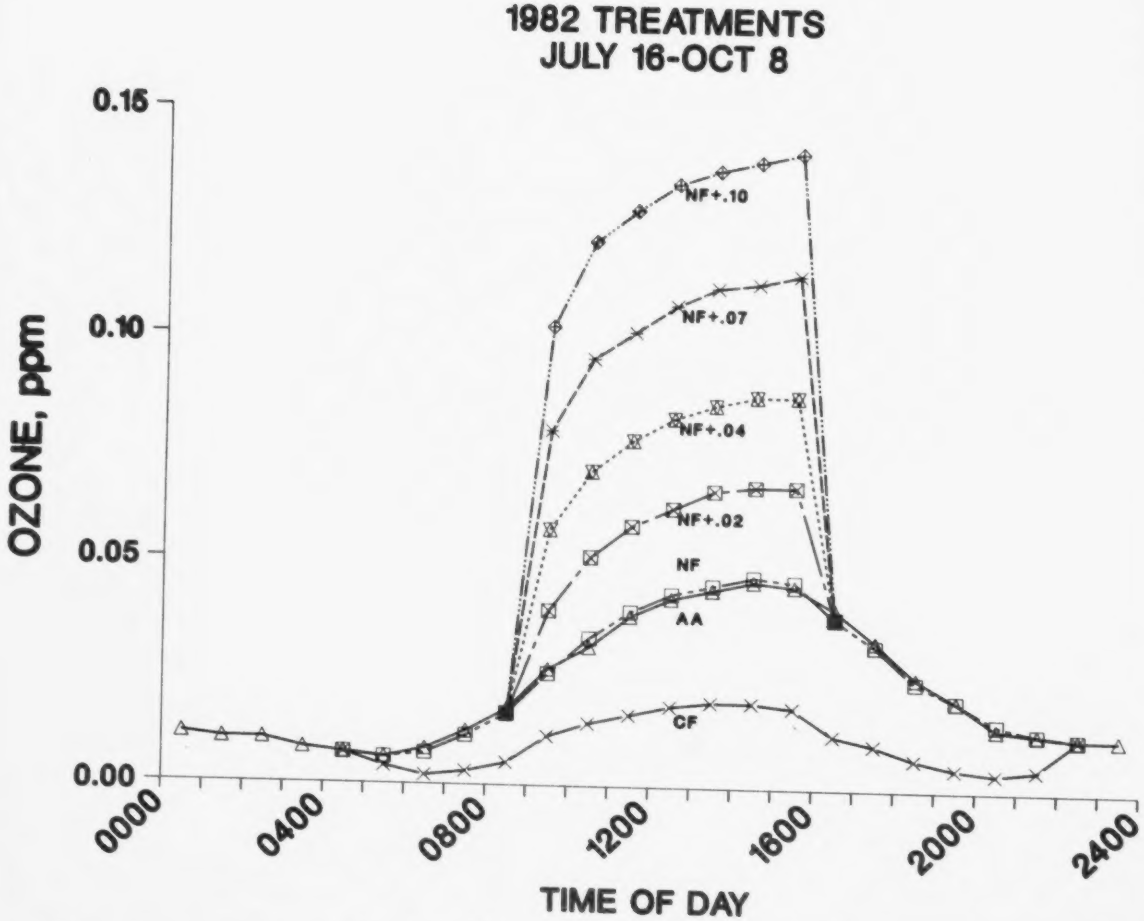

Figure 4.2.4.1. Mean O_3 concentrations in ambient air (AA), charcoal-filtered air (CF), or in non-filtered air chambers (NF) with various amounts of O_3 added for 7 h/day (0900-1600 CST) during the exposure period (10 July - 8 October 1982) at Argonne, Illinois. All chamber fans were turned off nightly from 2130-0530.

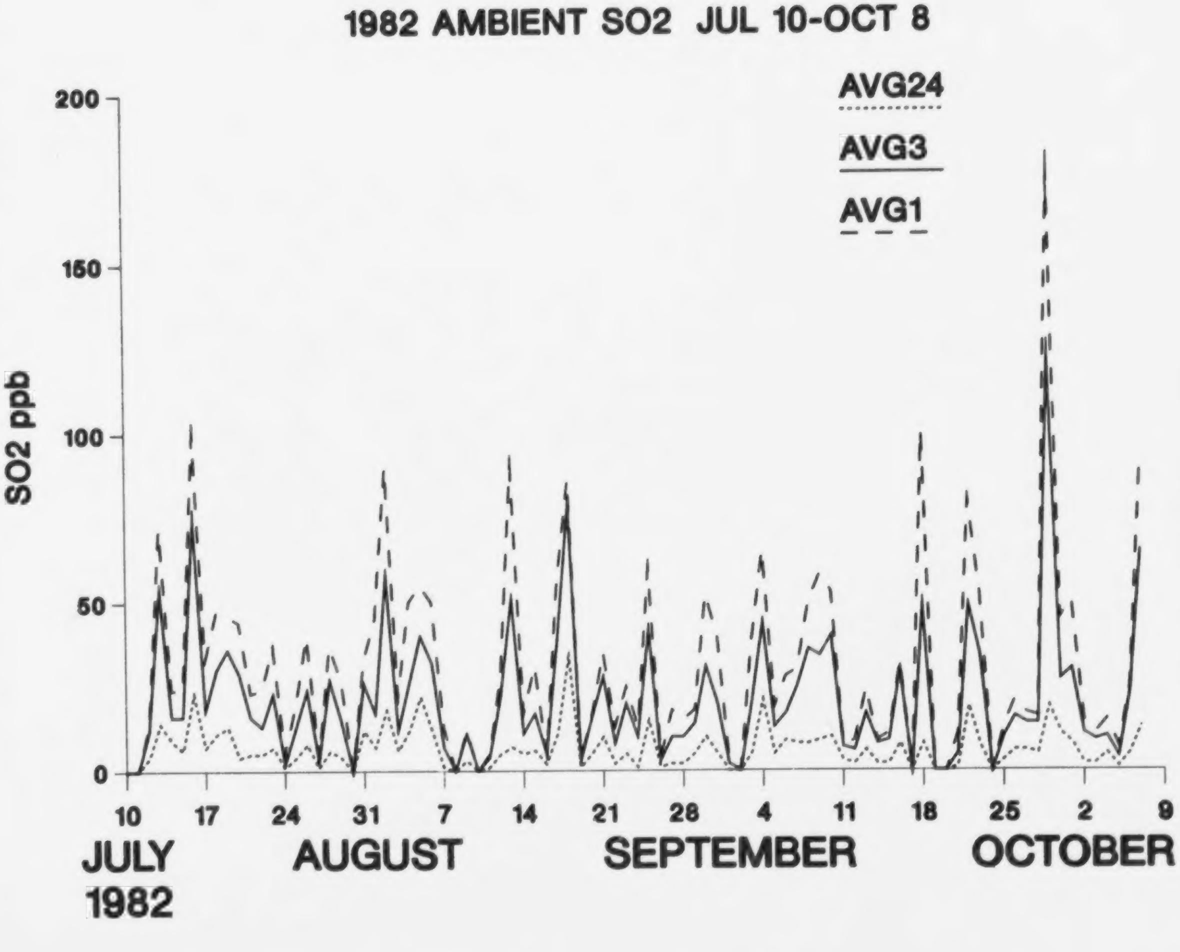

Figure 4.2.4.2. Ambient 24-h mean (average 24), 3-h peak mean (average 3), and 1-h peak mean (average 1) sulfur dioxide concentrations between 10 July and 8 October at Argonne, Illinois (1 ppm = 1000 ppb).

TABLE 4.2.4.3. PLANT HEIGHT AND MEAN PERCENT FOLIAR INJURY TO THE TOP FOUR LEAVES OF SORGHUM EXPOSED TO VARIOUS O_3 TREATMENTS FOR 85 DAYS IN OPEN-TOP CHAMBERS AT ARGONNE, ILLINOIS, IN 1982.

Treatment	Height*	Chlorosis**	Stipple	Necrosis	Total Injury
AA	1.13 m	20	10	4	34
CF	1.20	15	6	5	26
NF	1.20	17	5	2	24
NF + 0.02	1.20	10	6	5	21
NF + 0.04	1.18	20	5	5	30
NF + 0.07	1.18	25	7	10	42
NF + 0.10	1.20	19	16	23	58

* Each value is the mean of 12 plants (16 plants for the NF + 0.02 and NF + 0.04).

** Each value is the mean of 3 plants (4 plants for NF + 0.02 and NF + 0.04).

TABLE 4.2.4.4. RESULTS OF ANOVA TEST TO DETERMINE SIGNIFICANCE OF TREATMENT EFFECTS (MEAN SQUARES) AND REGRESSION ANALYSES OF DATA RESULTING FROM EXPOSURE OF GRAIN SORGHUM TO SEASONAL 7-H MEAN O_3 CONCENTRATIONS OF 0.016, 0.040, 0.059, 0.078, 0.102, AND 0.129 ppm BETWEEN JULY 16 - OCTOBER 8, 1982, AT ARGONNE, ILLINOIS.

Source		df	kg/ha	100-seed wt	Ambient† Plots
	Rep	2	369,326	0.0021	4083
	Treat	5	751,581*	0.0414**	1966
	Error	12	155,455	0.0021	2079
Weibull	alpha		8137.0	2.432	----
	sig		0.2963	0.2816	----
	c		2.217	2.576	----
	R^2‡		0.803	0.964	
Plateau-linear	c		8020.0	2.413	----
	B1		-16104.2	-4.167	----
	Theta		0.0615	0.0615	----
	R^2‡		0.829	0.991	

* $P < 0.05$.

* $P < 0.01$.

† Average yield (kg/ha) for the four companion plots surrounding each chambered plot.

‡ R^2 = the amount of the treatment sum of squares from the ANOVA accounted for by the model.

TABLE 4.2.4.5. YIELD RESPONSE OF GRAIN SORGHUM (DeKalb A28+) EXPOSED TO CHARCOAL-FILTERED AIR (CF), AMBIENT AIR IN OPEN PLOTS (AA), AND AMBIENT AIR PLUS O_3 BETWEEN JULY 16 - OCTOBER 8, 1982, AT ARGONNE, ILLINOIS.

Treatment	Seasonal 7-h Mean O_3 (ppm)	kg/ha	100-seed wt (g)*	No. Seeds/m
AA	0.039	8560	2.17	29977
CF	0.016	8282	2.43	25897
NF	0.040	7643	2.39	24301
NF + 0.02	0.059	8107	2.42	25455
NF + 0.04	0.078	7784	2.35	25170
NF + 0.07	0.102	7272	2.23	24780
NF + 0.10	0.129	6994	2.14	24836

* Each value is estimated from yield of 252 plants (336 plants NF + 0.02 and NF + 0.04).

The Weibull and plateau-linear model parameters are shown in Table 4.2.4.4. The R^2 values for kg/ha are relatively low probably because of the slightly greater yields in the NF + 0.02 and NF + 0.04 treatments compared to the NF treatment (Table 4.2.4.5). Neither model accounts for possible stimulations of yield. The plateau-linear model provides a slightly better fit to the data (as evaluated by R^2), but the Weibull model eliminates the "threshold concentration" below which no effects are expected. Yield reductions predicted from the Weibull equation are 2.5% at 0.06 ppm and 8% at 0.10 ppm O_3 (based on a 0.025 ppm control). The plateau-linear regression predicts a threshold for yield effects at 0.061 ppm O_3. The Weibull and plateau-linear regression equations are illustrated in Figure 4.2.4.3.

Regressing the yield against the other characterizations of O_3 exposure showed similar curves skewed to the right as the characterization goes from the seasonal 7-h average, peak daily hourly concentration averaged over the season, highest 7-h average, and the highest seasonal hourly value (Figure 4.2.2.8, previous section). Along with the regressions for the other crops studied (soybean, corn, wheat) these plots demonstrate that the loss estimates will be very similar irrespective of which of the four exposure estimates are utilized. They also demonstrate the extreme O_3 tolerance of sorghum compared to the other three crops.

While both sorghum and field corn both utilize the C_4 type of photosynthesis (soybean and wheat are C_3), it is not known whether this has any bearing on O_3 sensitivity. Sweet corn is also C_4 and several varieties have been shown to be rather sensitive to O_3 (Thompson, 1975; Thompson _et al_.,1976; Heagle _et al_., 1972; Cameron, 1975).

4.2.4.4 Conclusions

Sorghum is less sensitive to O_3 than soybean or wheat under the conditions of the experiments. While the apparent threshold for O_3 effects is lower for sorghum than field corn, sorghum is also considerably less sensitive than field corn once the threshold is exceeded.

4.2.5 Response of a Short-Season Barley Cultivar to O_3 (SWRCLAP -- Shafter, California)*

4.2.5.1 Introduction

Barley (_Hordeum vulgare_ L.) is one of the ten most important crops in the United States, with a cash value of approximately $1 billion in 1979. Yet relatively little is known of the dose-response of barley yield with O_3. Thus, the objective of this study was to assess the dose-response relationship between O_3 and yield of field-grown barley in open-top chambers. The barley variety chosen was 'Poco,' a six-rowed short-season, spring barley recommended for double cropping with cotton in the Southwest. The total acreage of this variety in California is small and, because of its short development time, it may not represent a typical barley response to O_3. for these reasons, the results of this study should be considered as preliminary information on the yield response of barley to O_3.

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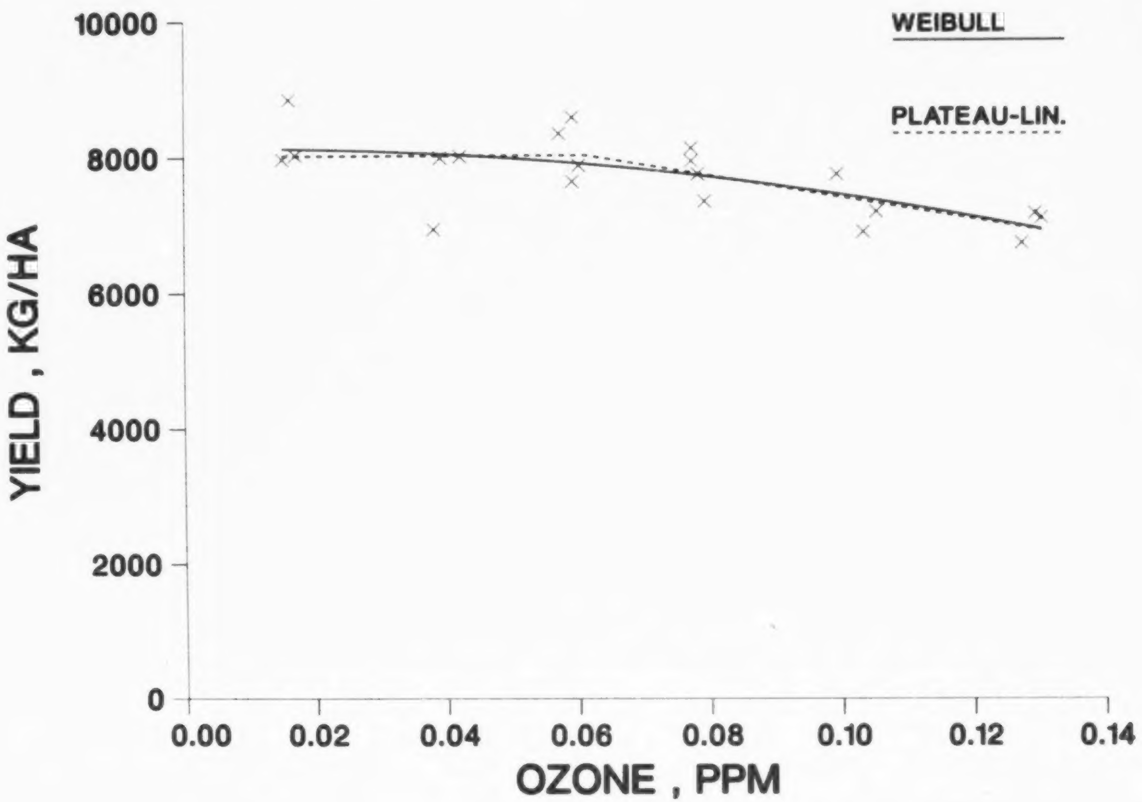

Figure 4.2.4.3. Exposure-response curves for seed yield of grain sorghum as a function of the seasonal 7-h daily average O_3 concentrations at Argonne, Illinois. Regression equations are:

Weibull -- $Y = 8137\, e^{-\left(\frac{O_3}{0.2963}\right)^{2.217}}$

Plateau-linear -- $Y = 8020 + \tau\,(-16104.2\,[O_3 - 0.0615])$

where

$O_3 < 0.0615$, then $\tau = 0$.
$O_3 > 0.0615$, then $\tau = 1$.

4.2.5.2 Materials and Methods

Cultural. Thirty individual plots were prepared for barley seeding on November 2, 1981, by incorporation of 67 kg/ha of 21-10-0 fertilizer into beds oriented north-south on 51 cm centers. Barley was seeded on November 5, 1981, using a 'Planet Junior' at the rate of 67.2 kg/ha on both beds and furrows, resulting in 25 cm row spacings. Plots were furrow-irrigated to field capacity between November 9-11, 1981. Irrigation was again required on February 22, 1982, when Irrometers read beween -250 to -300 mb. Total water (precipitation + irrigation) equalled 286 mm; precipitation during the growing season was 10 percent above normal for the area.

Twenty-four open-top chambers were placed on randomly chosen plots on January 28, 1982, when plants were approximately 20 cm in height and canopy cover was about 25%. Plants were spot-sprayed on February 2 with dilute detergent (5 ml Liquinox/11.3 l) to control powdery mildew. All plots were sprayed with Benlate (113 g/60 l) and Malathion 50 (120 ml/60 l) on February 8 for control of fungal pathogens and aphids. Severe symptoms of barley strip mosaic virus were occasionally observed, as were other foliar diseases. These symptoms precluded detailed evaluation of O_3 injury symptoms on barley foliage.

O_3 Treatments and Monitoring. O_3 addition began on February 16, 1982, just before anthesis. O_3 was added 7 h/day (0900-1600 LT), 5 days/week, for a total of 158 hours, until April 2, 1982. Treatments included (1) full charcoal filtration; (2) half-filtration; (3) no charcoal filter (NF); (4) NF x 1.3 ambient; (5) NF x 1.7 ambient; (6) NF x 2.0 ambient O_3 concentration. Four chambers were assigned each treatment in a competely randomized design. Concentrations in the O_3-added chambers were adjusted by a controller which was directed by millivolt input from a Dasibi O_3 analyzer monitoring ambient O_3 at 3 m height between plots. The controller signalled the Griffin O_3 generator to modulate voltage, hence O_3 output, in response to ambient O_3 concentrations. O_3 flow to each chamber was proportioned through flowmeters (Aalborg FM 112-02).

The controller was set to initiate generation of O_3 when ambient concentrations exceeded an hourly average of 0.03 ppm. During December 1981, the maximum 1 hour O_3 concentration exceeded 0.03 ppm only twice, and was generally below 0.02 ppm. From January 1 to February 15, 1982, hourly average O_3 concentrations exceeded 0.03 ppm only 3 times. Because O_3 was added as a proportion of ambient concentration, which was very low during this time, for practical purposes it was decided not to add O_3 until February 16, when ambient levels began to exceed 0.03 ppm on a regular basis. Plants were exposed to added O_3 for approximately 5% of the entire growing season.

Sample air from each chamber was collected at canopy height and drawn continuously at 4 l/min through dust-filtered (TE 38, 5 micron pore size; BGI, Inc., Waltham, Massachusetts) teflon lines which merged at a dual twelve-port rotary sample valve (Scanivalve Corporation, San Diego, California). Each valve stepped every two minutes so that every sample line was monitored for a total of five minutes per hour. Data from the two Dasibi O_3 analyzers monitoring the chambers and from the Dasibi monitoring ambient O_3 concentrations were logged with a Hewlett-Packard desk-top computer (HP 9830A) into magnetic tape and paper printout. Data were collected from 0800 to 1700 from February 16 to April 2, 1982.

Harvest. Barley was harvested on April 3, 1982. Uneven seeding and poor germination had resulted in significant variation in stand density from plot to plot and within chambers. This precluded harvesting on an area basis. Chambers were divided into four quadrants and 25 successive plants (crowns) were collected from the center row of each quadrant. Plants within 25 cm of chamber walls were not sampled nor were bird-damaged or diseased plants. Companion plots outside the chambers were not harvestd due to heavy bird feeding on these plants.

Top fresh weight of barley samples (four per chamber) were taken immediately after harvest. Dry head weights were taken at 10% moisture content. Number of heads per sample was recorded to determine relative sample size and amount of tillering. Samples were threshed by a motorized wheat thresher and weed weights and weights per 100 seeds were taken at 10% moisture content. Weight per 100 seeds was determined from four replicate samples by a mechanical seed counter (Old Mill Company, Model 850-2). Harvest data were analzyed by step-wise multiple regression and analysis of variance.

4.2.5.3 Results

O_3 Concentrations. Mean 7-h ambient O_3 concentration (0900-1600 PST) for the sampling period February 16 - April 2, 1982, was 0.046 ppm. Mean 7-h O_3 concentrations for the six chamber treatments were, in ascending order, 0.020, 0.030, 0.036, 0.055, 0.071, and 0.094 ppm (Table 4.2.5.1). Maximum hourly averages, seasonal average 1-h peak, and maximum 7-h averages are also given in Table 4.2.5.1. Fluctuations in daily 7-h O_3 averages are shown in Figure 4.2.5.1, and seasonal average diurnal curves for the 7-h period of O_3 addition are shown for each treatment in Figure 4.2.5.2. The O_3 monitoring period represented approximately 33% of the entire growing season. Ambient O_3 concentrations were at or below 0.03 ppm during the first 2/3 of the growing season.

Harvest Data. Average number of heads per plot, total weight per head, seed weight per head, and weight per 100 seeds for each treatment are given in Table 4.2.5.2. Results of a split-plot analysis of variance of these data are given in Table 4.2.5.3. Although number of heads (tillers) tended to be higher in the NF x 2.0 treatments, and seed weight per head and weight per 100 seeds tended to be lower than in the other O_3 treatments (Table 4.2.5.2), these differences were not statistically significant. Position within the chamber was significant, and samples collected in the northwest quarter had higher biomass than in other quarters. Regression analysis between harvest parameters and O_3 concentration expressed as seasonal 7-h mean, mean seasonal 1-h maximum, highest hourly mean, and highest single 7-h mean was not significant, except for cubic or higher polynomial terms of questionable biological significance.

TABLE 4.2.5.1. SUMMARY OF O_3 CONCENTRATIONS DURING EXPOSURE OF 'POCO' BARLEY AT SHAFTER, CALIFORNIA -- FEBRUARY 16 TO APRIL 2, 1982.

Treatment	Seasonal 7-h Mean	Highest 1-h Mean	Highest 7-h/day Mean	Mean of the Max. Hourly Average
CF	0.020	0.040	0.026	0.025
Half CF	0.030	0.053	0.041	0.036
NF	0.036	0.066	0.052	0.044
NF x 1.3	0.055	0.111	0.087	0.067
NF x 1.7	0.072	0.142	0.166	0.089
NF x 2.0	0.094	0.184	0.148	0.115

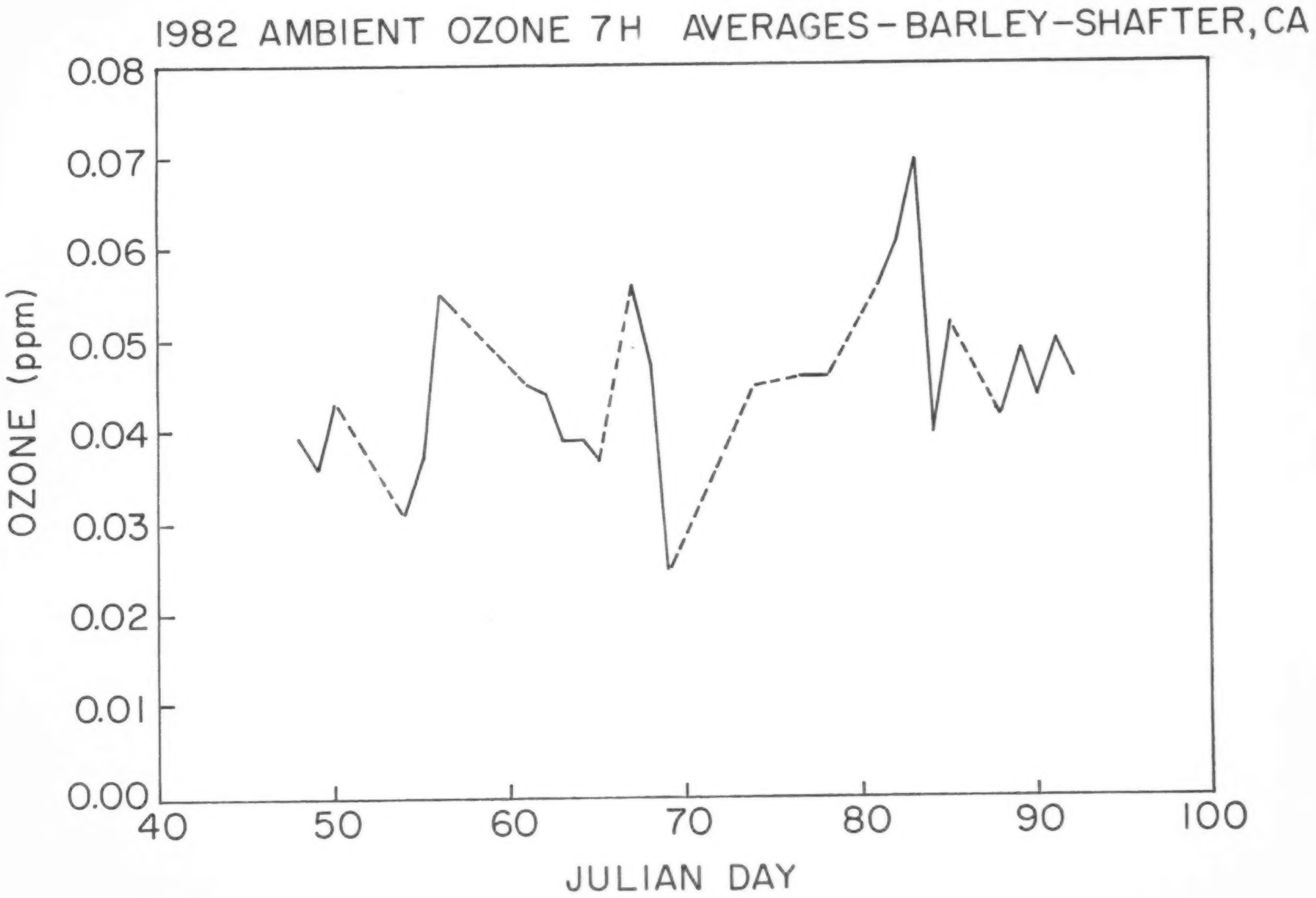

Figure 4.2.5.1. Daily 7-h ambient O_3 averages. Sold lines join points for successive days.

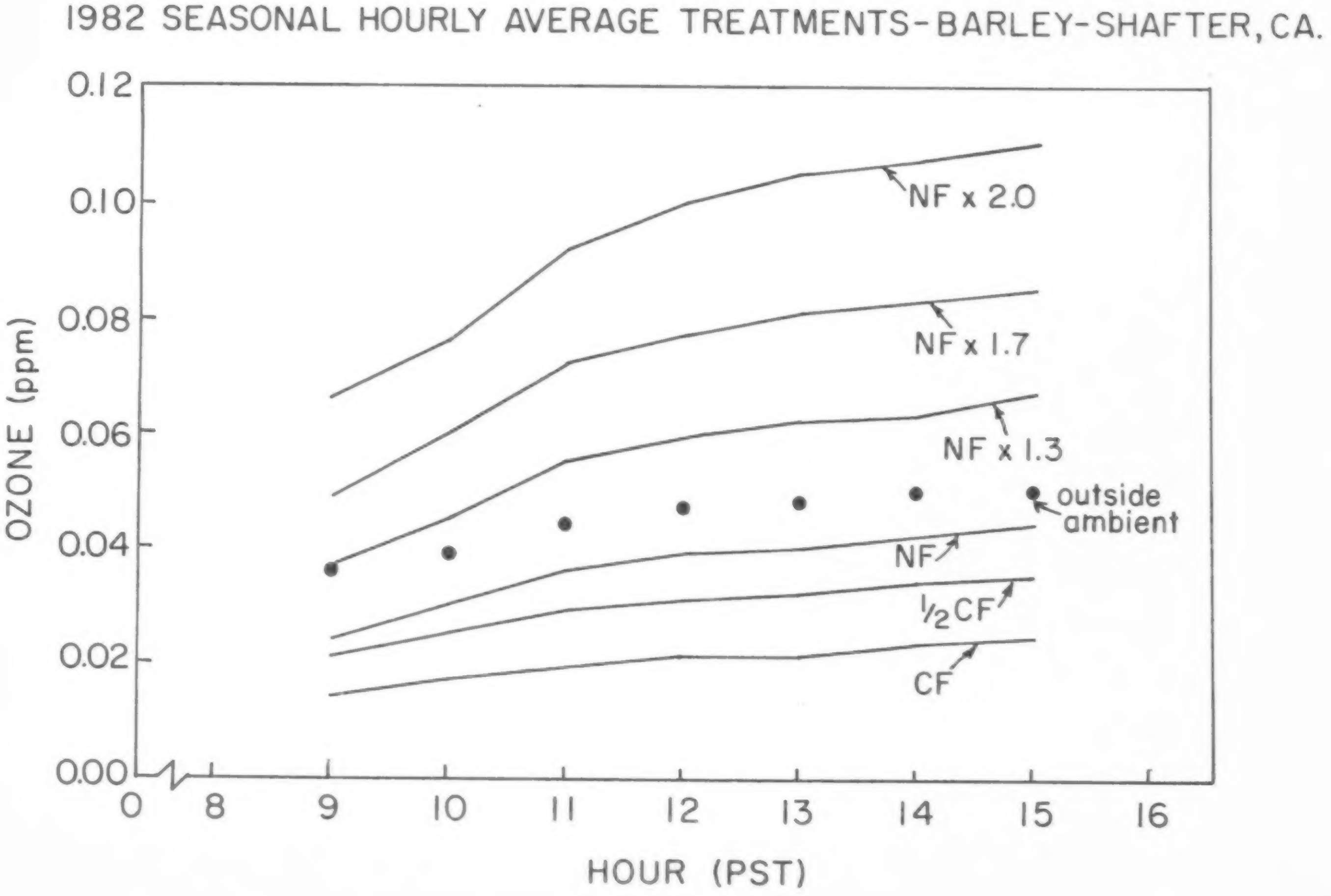

Figure 4.2.5.2. Diurnal curves of seasonal hourly O_3 means for each treatment, Shafter, California, 1982.

TABLE 4.2.5.2. HARVEST DATA FOR 'POCO' BARLEY EXPOSED TO O_3* IN OPEN-TOP CHAMBERS, SHAFTER, CALIFORNIA -- NCLAN 1982.

Treatment	O_3 (ppm)**	Number of Heads†	Weight per Head (g)†	Seed wt. per Head (g)†	Wt. per 100 Seeds‡
CF	0.020	857	1.93	1.30	2.83
Half CF	0.030	867	2.02	1.29	2.69
NF	0.036	876	1.98	1.28	2.74
NF x 1.3	0.055	826	2.06	1.29	2.75
NF x 1.7	0.072	874	1.92	1.27	2.71
NF x 2.0	0.094	1076	1.93	1.18	2.63

* O_3 added February 6 - April 2, 1982; 0900-1600 LT.

** Seasonal 7-h mean (0900-1600 LT).

† Mean of 25 plants/sample; 4 samples/chamber; 4 chambers/treatment.

‡ Mean of 4 replicates/sample.

TABLE 4.2.5.3. ANALYSIS OF VARIANCE FOR MEAN SQUARES OF 'POCO' BARLEY HARVEST DATA, SHAFTER, CALIFORNIA -- NCLAN 1982.

Source of Variation	df	No. of Heads	Wt. per Head	Seed Wt. per Head	Wt. per 100 Seeds
O_3 (O)	5	2557	444	339	699
Error a	18	5105	1056	230	351
Position in Chamber (P)	3	2755*	615	813**	2718**
P x O	16	662	236	85.3	94.2
Error b	54	781	273	63.4	119

* Significant at 5% level.

** Significant at 1% level.

4.2.5.4 Conclusions

Results of this experiment did not establish a statistically significant relationship between O_3 dose and yield of a short-term variety of barley. The plants had been exposed to added O_3 for only 158 hours during the growing season and this short exposure at relatively low concentrations may have been insufficient for expression of O_3 effect. This variety of barley appears to be unaffected by the relatively low O_3 concentrations present during the winter growing season in the Central Valley of California.

4.3 INFLUENCE OF SO_2 ON O_3 DOSE-RESPONSE RELATIONSHIPS

4.3.1 Dose-Response of Field Grown Tomato to Mixtures of O_3 and SO_2 (SWRCLAP)*

4.3.1.1 Introduction

Tomatoes are among the 10 most important crops produced in the U.S., with an annual cash value approaching 1 billion dollars. California captures approximately 90 percent of the processing tomato market and 30 percent of the fresh tomato market. There were 101,215 ha of processing tomatoes planted in California in 1981 with a total value of 303 million dollars, of which 10,158 ha were planted in San Joaquin County with a value of 32 million dollars, the third highest in the state.** Approximately 25 to 32 percent of this hectarage was planted with the variety 'Murietta.'†

Most of California's tomato hectareage is located in the Central Valley near San Joaquin County, directly downwind from the large urban/industrial complex around San Francisco Bay. Proposed fossil-fuel burning power plants in the area (California Energy Commission, 1982) could contribute to air pollution levels in this agriculturally important area. This experiment was designed to evaluate the potential impact on tomato productivity of O_3 and SO_2, which may be present together in this part of the Central Valley of California.

4.3.1.2 Materials and Methods

Site Description. The experimental site was located on the south-central edge of a 160 ha commercial tomato farm, owned and operated by John Paulsen, 700 Linne Road, Tracy, California. The weather in 1981 was very typical with essentially no deviation from the 20-yr normal. The weather in 1982, however, was cool and moist. Cooling degree-days were 36% lower and precipitation 7.5 cm higher than in 1981.

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* P. J. Temple, K. A. Surano, R. G. Mutters, G. E. Bingham, J. R. Kercher, and J. H. Shinn.

** Personal communication. D. Shepard. San Joaquin County Agricultural Commissioner's Office, Stockton, California.

† Personal Communication. G. Terry, Tri Valley Growers, Modesto, California.

The soil at the site is a CW-capay clay (a fine montmorillinitic thermic typic chromoxerert), wet, with a 0 to 2 percent slope (Class I). It is a deep alluvial soil derived from sedimentary rock, with a slow permeability rate and high available water capacity. Soil sampling was conducted in November 1981. Results indicated that the field site was variable with regard to pH and electroconductivity, but that available nutrients were within the optimum range for tomato production.

Field Arrangement. 1981 Design -- The 39.6 m by 61.0 m experimental site, with a 9.1 m buffer zone of tomatoes on all sides, was divided into 32 identical 56.3 m plots in 4 east-west rows of 8 plots each, bisected by a 9.1 m east-west strip for the instrument trailer and field access. Each plot contained one randomly placed open-top fumigation chamber and one associated companion plot of 3 m length on one row of tomatoes. One tensiometer (Jet-Fill model 2725, Soil Moisture Equipment Corporation, Santa Barbara, California) was placed mid-row at 60 cm depth in each chamber to measure soil water potential. Partial rows of plants occurred within the chambers on the north and south sides, but these plants were treated as buffers and were not harvested. Pollution level treatments for each chamber were selected at random.

1982 Design -- The field arrangement was very simliar to that for 1981. Rows of tomatoes again ran in an east-west direction and the 32 plots were divided the same as in 1981. Treatments were again randomly located in the plots with the tomato double row bisecting the east-west diameter, but the number of companion plots was increased to 48 and distributed as evenly as possible for more accurate determination of field variability. Tensiometers were placed as in 1981. Pollution levels were again assigned at random except the controls which were assigned the same positions as in 1981, because of dispensing line restrictions.

Crop Establishment. 1981 -- The tomatoes were seeded on 1 June at the rate of 0.6 kg/ha into prepared single row, false furrow, 1.68 m beds running east-west to which preplant fertilizer and pesticide treatments had been applied (Table 4.3.1.1). The field was then irrigated using the false furrows adjacent to the seed row to foster germination. Germination occurred on 17 June. Seed rows were worked into elevated 50-cm wide beds, cultivated, and side dressed with 120 kg/ha N as NH_3 on 6 July, when the sixth trifoliate leaf was fully expanded (15 cm tall). The crop received no further cultivation or fertilizer application. After the beds were established, the plot was irrigated for 8 h on each side of the row. Chamber and companion plot density averaged 11.8 and 12.2 plants per meter, respectively.

The test plots were furrow irrigated and sprayed during the growing season as part of the farmer's regular schedule (Tables 4.3.1.2 and 4.3.1.3). Water was always applied before any of the plot tensiometers reached -0.6 bars soil water potential. No irrigation was applied for 3 weeks prior to harvest to increase the percent solids within the fruit. Chamber fans were shut down during aerial application of pesticides to allow the spray drift to settle into the chamber in a similar manner as the field. Blowers were started 5 minutes after spraying was completed.

TABLE 4.3.1.1. CROP CULTURAL PRACTICES FOR TOMATO AT TRACY, CALIFORNIA IN 1981 AND 1982.

Operation	Description	1981	1982
Tillage	Plow, disc, level	Oct/April	Nov/April
Bed preparation	Preplant tillage-bedshape	23 April	27 April
Fertilization	280 l/ha of liquid 8-24-6 shanked in below seed row	23 April	27 April
	112 kg/ha N as anhydrous NH_3 side-dressed at last cultivation	07 July	28 June
Nematocide	E-D-Bee (ethylene dibromide) at 28 l/ha shanked in below seed row	23 April	27 April
Planting	Drilled at 0.6 kg/ha (target = 13 plants/meter)	01 June	17 May
Herbicide	3.8 l/ha Devorinol 2.8 l/ha Tillum 1.9 l/ha Treflan	23 April 23 April ---	27 April 27 April 28 June
Irrigation	Seed bed soaking from false furrow	01 June	24 May
Final bedding	Cultivate, pack bed	07 July	28 June

TABLE 4.3.1.2. IRRIGATION SCHEDULE FOR TOMATOES AT TRACY, CALIFORNIA IN 1981 AND 1982.

1981	1982
01 June	24 May
13 June	01 June
28 June	17 June
14 July	01 July
30 July	15 July
14 Aug	29 July
29 Aug	14 Aug
	12 Sept

TABLE 4.3.1.3. AERIAL PESTICIDE APPLICATION SCHEDULE DURING TOMATO EXPERIMENT AT TRACY, CALIFORNIA IN 1981 AND 1982.

Dusting Date	Agent	Application
1981		
01 July	Lannate	0.8 kg/ha
18 Aug	Lannate	0.5 kg/ha
18 Aug	Thiodien	0.5 kg/ha
04 Sept	Ethrel	4.7 l/ha
1982		
05 Aug	Sulfur dust	45 kg/ha
28 Aug	Lannate	0.5 kg/ha
23 Sept	Bravo	1.0 kg/ha
27 Sept	Ethrel	4.7 l/ha

The tomato fruit did not ripen as rapidly as would normally be expected. When it was determined that the crop would not ripen for more than 3 weeks after the normal harvest date, the field was sprayed with 4.7 l/ha of Ethrel to terminate vegetative growth and stimulate ripening. Chambers were hand sprayed, with fans off, to apply the same treatment levels as the outside plants had received. Harvest was 2 weeks after application on 4 September.

1982 -- The tomatoes were seeded directly on 17 May into prepared double row, false furrow beds. Seeding rate, target plant density, bed width, row orientation, seed row irrigation, and preplant treatments were the same as those employed in 1981 (Table 4.3.1.1). The chamber and companion plot mean plant densities were 19.3 and 18.6 plants per meter, respectively. Although the plant densities in 1982 were significantly greater than those in the 1981 experiment, the total biomass per plot was virtually equal in both years. Germination occurred on 7 June. Final cultivation and side dressing was performed on 30 June. Fertilization was the same as in the 1981 season; however, 1.9 l/ha Treflan (herbicide) was applied on June 28. Ethrel was aerially applied at 4.7 l/ha to plots and adjacent field on 27 September. Fans were turned off to allow a more uniform distribution within the chamber. Harvest began on 11 October, 2 weeks after Ethrel application.

Treatments. The experiment consisted of 5 levels of O_3 and 6 levels of SO_2 in a 5 x 6 completely randomized factorial design. The control treatment (no O_3/no SO_2) was replicated 3 times. Except for occasional interruptions (Table 4.3.1.4), fumigation continued 7 d/wk from initial crop exposure through harvest.

1981 Exposure Levels -- The 5 treatments of O_3 were: charcoal filtered (CF), nonfiltered (NF), NF + 0.03 ppm O_3; NF + 0.06 ppm, and NF + 0.09 ppm. O_3 was produced from compressed oxygen using a Griffin Model GTC-1A O_3 generator. Voltage supplied to the Griffin was governed by an external controller, based upon the ambient O_3 levels at canopy height. O_3 was supplied to the required treatment from 0900-1600 PST daily. Fumigation began on 15 July 1981, approximately 2 weeks after flower initiation, and continued until 14 September 1981. Chamber O_3 concentrations were monitored by 3 Dasibi Model 1003-AH O_3 analyzers on a timesharing system. Ambient O_3 concentrations were continuously monitored by a fourth Dasibi. These Dasibis were calibrated with a fifth Dasibi designated as a transfer standard by the California Air Resources Board Laboratory, Sacramento.

The SO_2 levels were: CF (0.006 ppm), 0.016 ppm, 0.032 ppm, 0.064 ppm, 0.116 ppm, and 0.227 ppm. The SO_2 treatments were achieved by mixing 100% anhydrous SO_2 with compressed air to provide approximately a 20% SO_2 air stream. This was then divided between the fumigation chambers using individual flowmeters and distribution lines. Fumigation began on 18 July and continued until 14 September. Chamber SO_2 concentrations were monitored by three TECO Model 43 pulsed fluorescent SO_2 analyzers on a timesharing basis. Ambient SO_2 was continuously monitored by a fourth TECO.

Two SO_2 fumigation routines were used during the 1981 season. Initially, an automatic control system was to be available to generate 2 daily peaks, the larger occurring in the morning and the lesser in the late afternoon. This "natural" series was to include the period from 0600-1900 PST daily. However,

TABLE 4.3.1.4. FUMIGATION INTERRUPTIONS DURING THE TOMATO EXPERIMENT AT TRACY, CALIFORNIA, IN 1981 AND 1982.

Date	Gas	Cause	Time Loss
1981			
29 July	O_3	Constant head system removed	2.5 h
29 July	SO_2	Constant head system removed	4 h
10-12 Aug	Both	Power system conversion	2 d
15-16 Aug	Both	Line loss check	2 d
21 Aug	O_3	Griffin failure	1 d
02 Sept	SO_2	Air compressor failure	3 h
04 Sept	Both	Power failure	1 d
09 Sept	SO_2	Air compressor failure	1 h
1982			
22 July	SO_2	Clogged lines	7 h
24 July	O_3	Griffin failure	4 h
25 July	O_3	Controller test	3 h
29 July	SO_2	Plumbing change	7 h
31 July	SO_2	Line condensation	2 h
04 Aug	Both	Analyzer repair	7 h
06 Aug	O_3	Leak in Griffin	1 h
10 Aug	O_3	Griffin failure	1 h
16 Aug	O_3	Griffin failure	2 h
30 Aug	Both	Analyzer repair	2 h
31 Aug	Both	EPA audit	5 h
01 Sept	O_3	EPA audit	2 h
02 Sept	O_3	Griffin failure	1 h
3-10 Sept	O_3	Griffin failure	7 d
24 Sept	O_3	Griffin failure	3 h
26 Sept	Both	Computer failure	6 h
28 Sept	Both	Analyzer repair	7 h
03 Oct	Both	Scanivalve failure	6 h
07 Oct	Both	Power failure	5 h

the controller was nonoperational on the first day of fumigation, and a conventional square-wave was substituted. When the controller was still not available after 2 weeks of fumigation, the SO_2 time series was changed to one more consistent with other NCLAN sites (0900-1600). Early season control problems and this change in fumigation routine resulted in an unusual season average exposure curve.

1982 Exposure Levels -- The 5 treatments of O_3 were: CF, NF, NF x 1.3, NF x 1.6, NF x 2.0, where NF represents the ambient level outside the chambers. O_3 was introduced as a multiplicative function of ambient concentration, in contrast to the additive approach used in 1981, to simulate normal diurnal curves of O_3 concentration. O_3 addition was based on ambient levels at canopy height. O_3 generation and daily delivery times were the same as in 1981. Fumigation began on 21 July 1982, one week after flower initiation, and continued until 11 October 1982.

The 6 levels of SO_2 in 1982 were: CF (0.002 ppm), 0.029 ppm, 0.050 ppm, 0.073 ppm, 0.116 ppm, and 0.229 ppm. Fumigation began on 27 July 1982. Treatments were initially achieved using compressed air tanks containing 20% SO_2. However, due to rapid tank exhaustion, the system of mixing 100% anhydrous SO_2 and air was reemployed on 29 July. Plant exposure occurred daily from 0800-1500 PST. A square wave SO_2 fumigation routine was used.

Quality Assurance. Two of the O_3 analyzers were certified as transfer standards by the California State Air Resources Board in 1981 and all analyzers passed EPA audits in both 1981 and 1982. Routine calibrations were conducted on all gas analyzers throughout both seasons in accordance with NCLAN protocols.

Line loss calibrations were performed for both years at the beginning and end of the season and data corrected accordingly. Length of sample lines accounted for an average 13% loss of O_3 samples in 1982. No O_3 loss was detected in 1981 and no SO_2 loss was detected in both years.

Injury Symptom Evaluation. Estimates of visible plant responses to O_3 and SO_2 were made on all treatments. Plant heights were measured, and plant vigor and condition of foliage were visually estimated for each chamber. No visible O_3 or SO_2 injury symptoms were observed, nor did plant height or plant vigor correlate with O_3 or SO_2 dose.

Harvest. 1981 -- The tomatoes were harvested on 15-18 September 1981. All companion plots were harvested prior to the enclosed plots, to allow the large number of green fruit to ripen within the chambers. Because these fruits were in the early stage of ripening, it was considered best to terminate all plots at a similar ripening stage. Harvest of the research site and the adjacent commercial field began the same day.

One single row bed 3-m long was harvested in all plots. Border rows were removed before harvest. Tomatoes plants were cut at soil level, placed in a plastic-lined 100-l can, and shaken to remove fruit. Fruits were counted and manually sorted using the same color standard employed by commercial harvesters. Uniform techniques were applied to both companion and chambered plots.

Data were collected on fresh weight, dry weight, and number of marketable green and red tomatoes and on fresh and dry weights of foliage, including all stems and leaves. An 11-l sample was taken from both the green and red harvested tomatoes, cut in quarters, placed in stainless steel trays, and dried at 60°C in a convection oven to obtain dry weight. All harvested foliage was placed in burlap bags and dried for 72 h at 60°C.

1982 -- Tomatoes were harvested on 11-24 October 1982. Techniques employed and data collected were the same as those in 1981, with the following exceptions: one double-row bed 3-m long was harvested in all plots. A 2-l aliquot of both green and red fruit was pureed, then quantitatively transferred to stainless steel trays and dried at 60°C. A subsample of the total foliage harvested from each plot was dried at 60°C for 72 h to determine dry weights.

Data Analyses. Harvest Data -- During both years, salt accumulation and Verticillium wilt severely impacted yield of some treatments within the experimental field. Treatments affected in 1981 were a control, NF O_3/0.016 ppm SO_2, NF + 0.09 ppm O_3/0.227 ppm SO_2. In 1982, the affected treatments were a control and CF (O_3)/0.073 SO_2. Harvest data from these treatments were not included in the statistical analyses, but estimates of these treatment totals were made following the procedures of Steele and Torrie (1980). Total degrees of freedom in the analysis of variance was adjusted for these estimates. For the analysis of variance, the data were analyzed as a 2 x 5 x 6 factorial experiment in a completely randomized design. The two years were thus treated as replicates.

Harvest data for each year were analyzed by step-wise multiple regression. Independent variables included in the regression model were number of plants, companion plot number of red fruit, companion plot total fruit number, companion plot red fruit fresh weight, companion plot red fruit dry weight, companion plot total fruit fresh and dry weights, companion plot plant (stem + foliage) dry weight, seasonal 7-h average O_3 concentration (ppm), seasonal 7-h average SO_2 concentration (ppm), $[O_3]^2$, $[O_3]^3$, $[SO_2]^2$, $[SO_2]^3$, and the multiplicative term $[O_3] \times [SO_2]$. Dependent variables included in the regression analyses were number of red fruit, ratio of red to green fruit, total fruit number, total fruit fresh weight, plant (stem + foliage) dry weight, average number of red fruit per plant, and average fresh weight of red fruit per plant. Total fruit fresh weight was selected as the most representative of marketable yield.

4.3.1.3 Results and Discussion

Air Quality. Summaries of O_3 and SO_2 concentrations averaged across treatments are given in Table 4.3.1.5 for 1981 and in Table 4.3.1.6 for 1982. Seasonal 7-h mean O_3 concentrations in 1981 were 0.012, 0.038, 0.062, 0.085, and 0.102 ppm for CF, NF, NF + 0.03, NF + 0.06, and NF + 0.09 ppm treatments, respectively. Seasonal mean diurnal curves for these treatments are shown in Figure 4.3.1.1. Seasonal trends in ambient O_3 concentrations in 1981 are shown in Figure 4.3.1.2. Seasonal 7-h mean O_3 concentrations were lower in 1982, averaging 0.012, 0.031, 0.041, and 0.051 ppm for CF, NF, NF x 1.3, NF x 1.7, and NF x 2.0 treatments, respectively. Seasonal mean diurnal curves for these treatments are shown in Figure 4.3.1.3, and daily 7- and 24-h mean

TABLE 4.3.1.5. SUMMARY OF O_3 AND SO_2 CONCENTRATIONS DURING THE 1981 TOMATO EXPERIMENT AT TRACY, CALIFORNIA.

Treatment	Average* Conc.	Average** Peak	Peak† 1	Peak‡ 2
		O_3 (ppm)		
CF	0.012	0.018	0.044	0.042
NF	0.038	0.043	0.086	0.085
NF + 0.03	0.062	0.072	0.114	0.110
NF + 0.06	0.085	0.092	0.134	0.131
NF + 0.09	0.102	0.107	0.163	0.160
Ambient	0.032	0.043	0.093	0.092
		SO_2 (ppm)		
CF	0.006	0.007	0.020	0.018
0.03	0.016	0.017	0.159	0.135
0.06	0.032	0.050	0.154	0.142
0.09	0.064	0.079	0.303	0.294
0.15	0.116	0.140	0.417	0.375
0.39	0.227	0.262	0.516	0.501
Ambient	0.004	0.009	0.025	0.024

* Seasonal 7 h average (0800-1500 PDT).

** Average daily 1 h peak.

† Highest hourly average.

‡ Second highest hourly average.

TABLE 4.3.1.6. SUMMARY OF O_3 AND SO_2 CONCENTRATIONS DURING THE 1982 TOMATO EXPERIMENT AT TRACY, CALIFORNIA.

Treatment	Average** Conc.	Average** Peak	Peak† 1	Peak‡ 2
		O_3 (ppm)		
CF	0.012	0.024	0.082	0.077
NF	0.031	0.051	0.105	0.099
NF x 1.2	0.041	0.065	0.142	0.137
NF x 1.4	0.047	0.076	0.192	0.180
NF x 1.5	0.051	0.084	0.223	0.212
Ambient	0.034	0.061	0.181	0.178
		SO_2 (ppm)		
CF	0.002	0.007	0.020	0.019
0.03	0.029	0.048	0.203	0.182
0.06	0.050	0.075	0.466	0.245
0.09	0.073	0.107	0.455	0.402
0.15	0.116	0.158	0.567	0.508
0.39	0.229	0.281	0.657	0.593
Ambient	0.004	0.004	0.015	0.014

* Seasonal 7 h average (0800-1500 PDT).

** Average daily 1 h peak.

† Highest hourly average.

‡ Second highest hourly average.

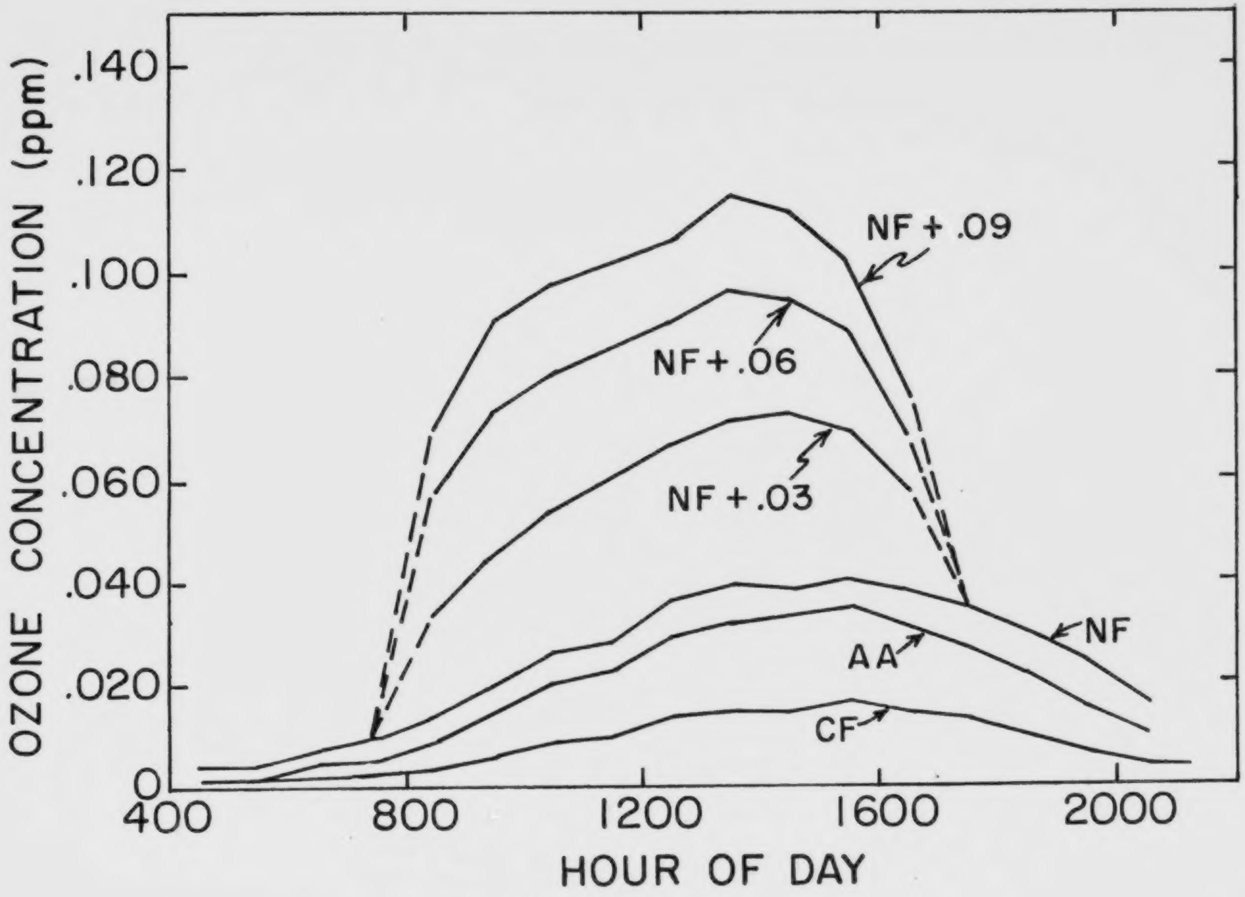

Figure 4.3.1.1. Diurnal curves of seasonal mean O_3 concentrations for 1981 O_3 treatments, Tracy, California.

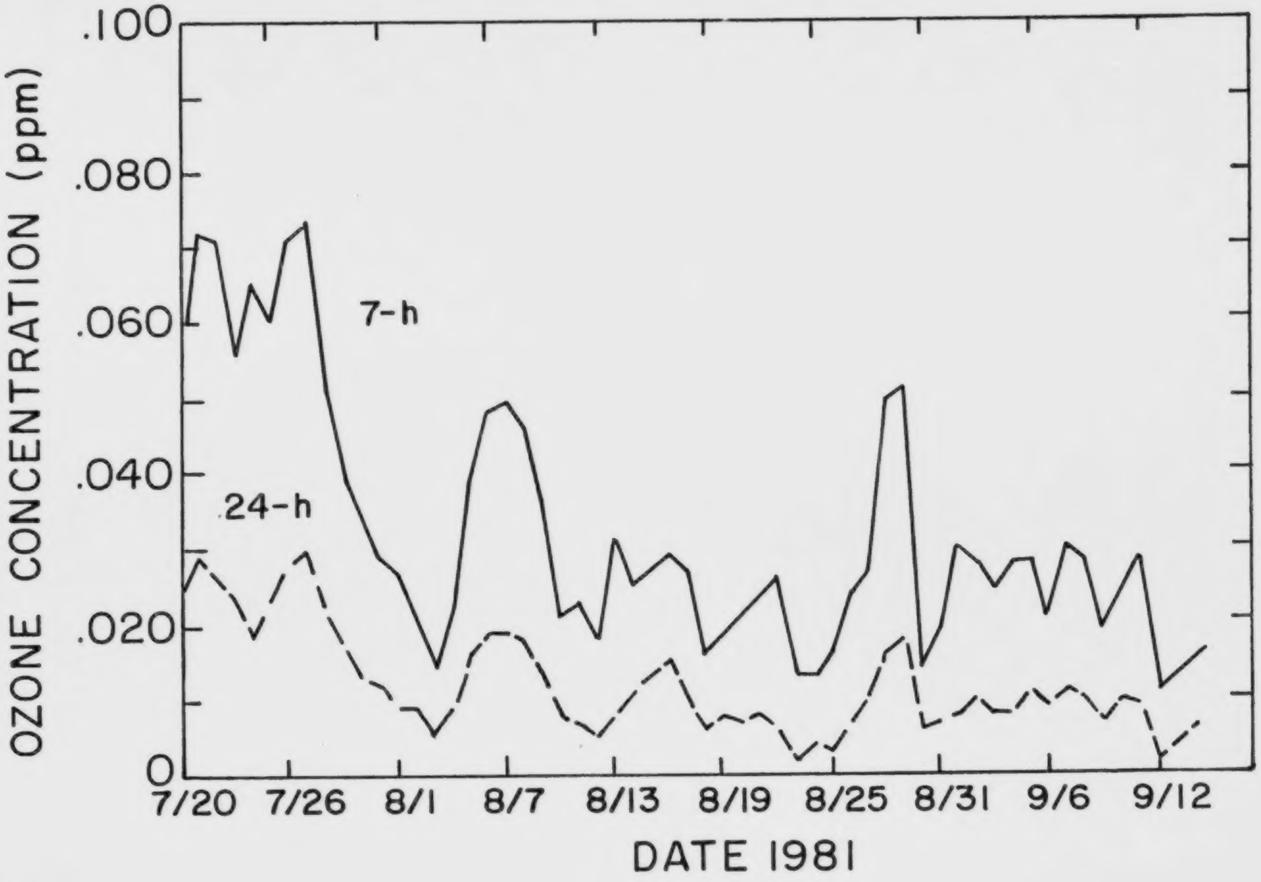

Figure 4.3.1.2. Daily 7 and 24-h ambient O_3 concentrations at Tracy, California, 1981.

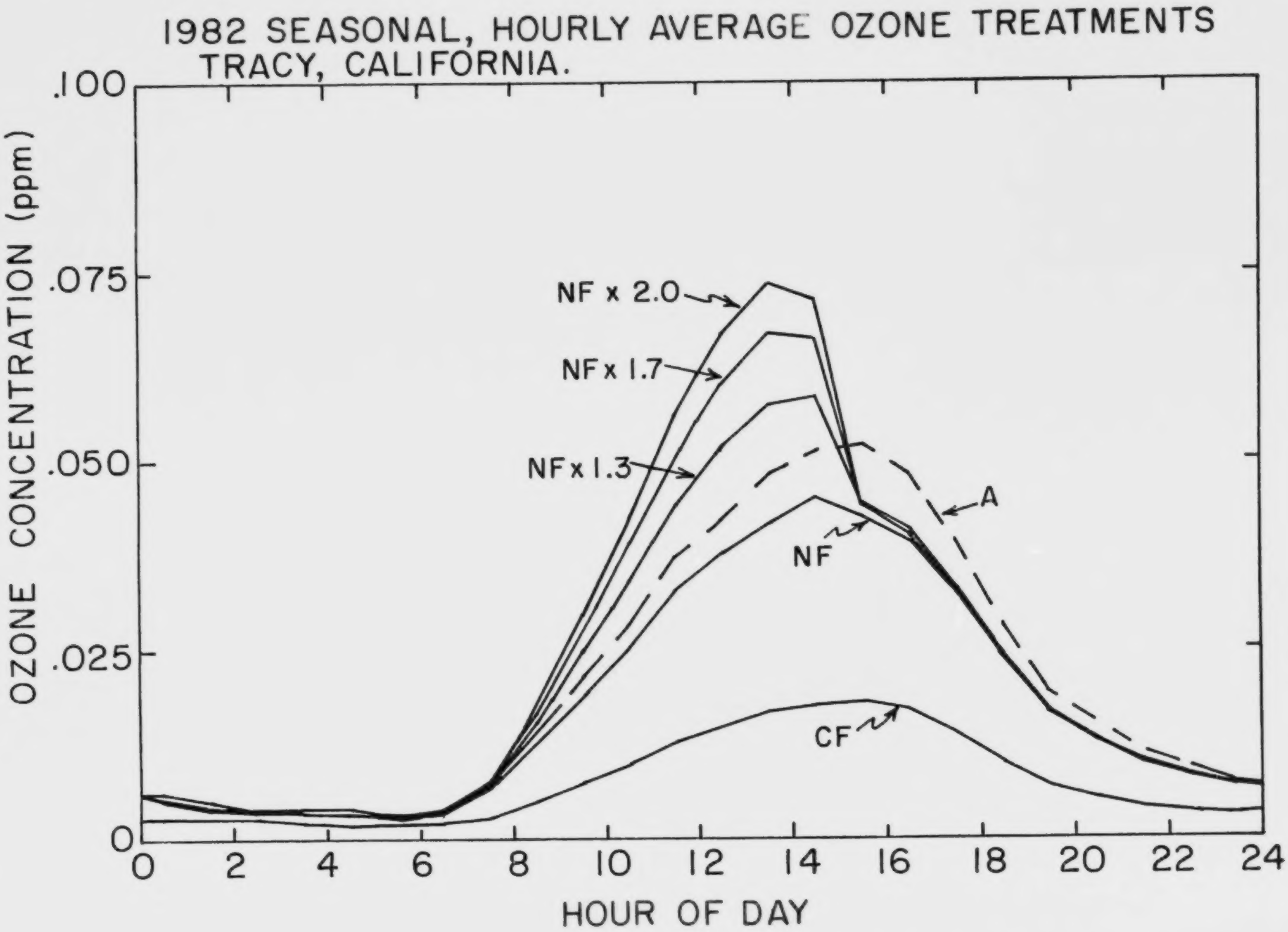

Figure 4.3.1.3. Seasonal mean diurnal curves for O_3 treatments in 1982, Tracy, California.

concentrations for 1982 are shown in Figure 4.3.1.4. Lower O_3 concentrations in 1982 were attributable to lower ambient O_3 levels, the change from additive to proportional O_3 additions, and to a 10-day failure of the O_3 generating system in September (Table 4.3.1.4).

Seasonal 7-h means for the 6 SO_2 treatments in 1981 were 0.006, 0.016, 0.032, 0.064, 0.116, and 0.227 ppm. In 1982, seasonal 7-h means for SO treatments were 0.002, 0.029, 0.050, 0.973, 0.116, and 0.229 ppm. Seasonal mean diurnal curves for SO_2 treatments are shown for 1981 in Figure 4.3.1.5, and for 1982 in Figure 4.3.1.6.

Chamber Effects. A comparison between the companion plots and chambers with ambient O_3 and less than 0.05 ppm SO_2 showed that there were significantly fewer green tomatoes in the companion pots (14% unripened in 1981 and 6% in 1982) than in the chambers (21% unripened in 1981 and 34% in 1982). This difference in ripening occurred because the farmer's aerial application of a ripening agent (Ethrel) was apparently not able to penetrate the chambers uniformly. In 1981 hand spraying in the chambers reduced this difference, but in 1982 hand spraying with ripening agent was not attempted. Since the commercial operation could effectively ripen the tomatoes when harvest was near, the degree of ripening was not considered important in our final analysis of yield. The companion plots also had larger yields of total fruit (fresh weight) than the chambers (12% greater in 1981, and 24% greater in 1982). This large difference was significant and represents an estimate of a chamber environmental effect.

The mean yield of total fruit (fresh weight) of companion pots was 67 ton/ha in 1981 and 64 ton/ha in 1982. These yields are not significantly different considering the natural variation in the field. Coefficients of variation (ratio of standard deviation to the mean) of total fruit yield in companion plots was 0.15 in 1981 and 0.19 in 1982.

Dose-Response. Tomato yield expressed as total fruit (fresh weight) across O_3 and SO_2 treatments are given in Table 4.3.1.7 for the 1981 harvest and in Table 4.3.1.8 for the 1982 harvest. Analysis of variance for combined data from both years is shown in Table 4.3.1.9. O_3 had a highly significant effect on yield ($p < 0.01$), and SO_2, year, and year x SO_2 interaction were also significant ($p < 0.05$). The O_3 x SO_2 term was not significant, indicating that O_3 and SO_2 did not interact in reducing yield of tomatoes in the experiments. Step-wise regression between tomato fresh weight and independent variables previously listed supported this conclusion. In both 1981 and 1982, the most significant variable explaining yield was the square of the seasonal 7-h mean O_3 concentration, followed by the seasonal 7-h mean SO_2 concentration. The O_3 x SO_2 multiplicative term was not significant, indicating an additive response of tomato to O_3 and SO_2 mixtures. Companion plot terms were not significant in 1982, but companion plots were significant in 1981, and the coefficient of the companion plot term was factored into the constant of the 1981 regression equation.

These regression equations are given in Table 4.3.1.10. Regression with O_3 and SO_2 explained 67% of the variation in treatment yields in 1981, and 46% of yield variation in 1982.

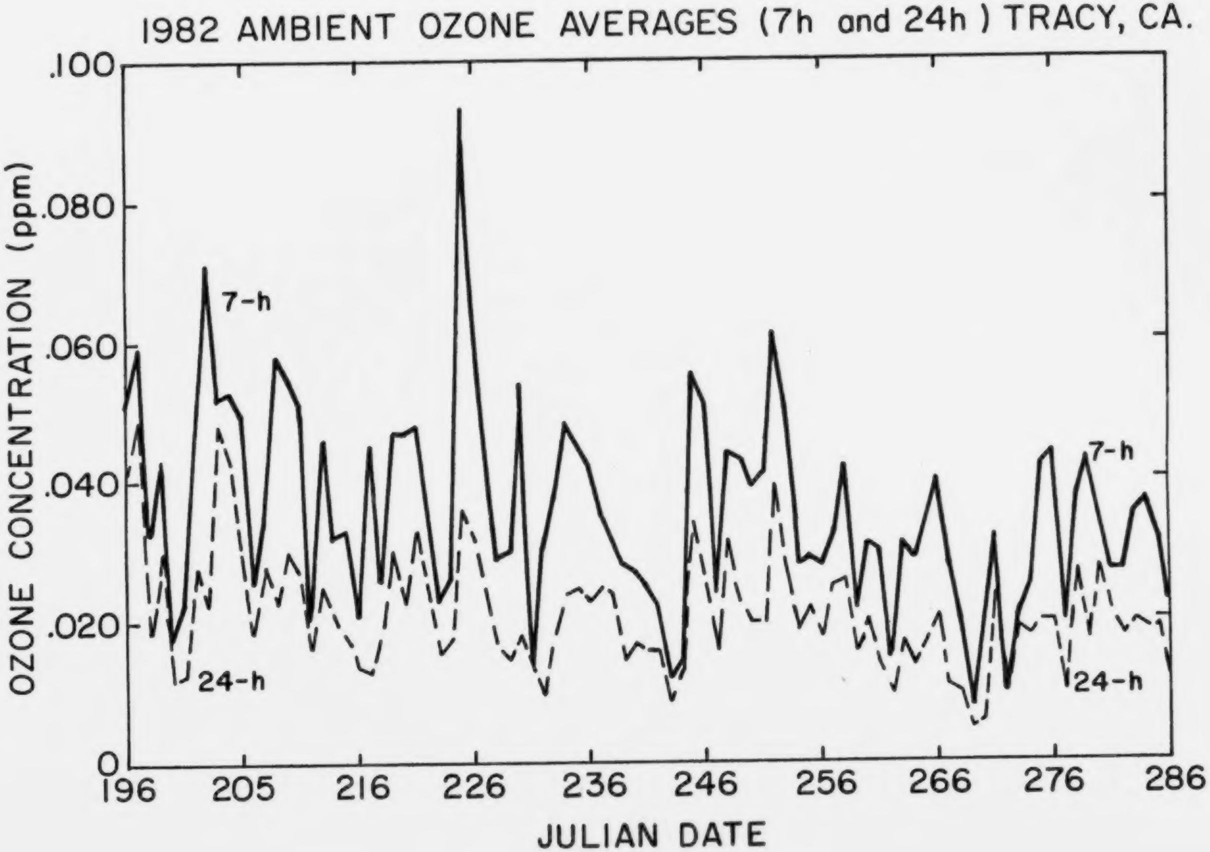

Figure 4.3.1.4. Daily 7- and 24-h ambient O_3 concentrations at Tracy, California, 1982.

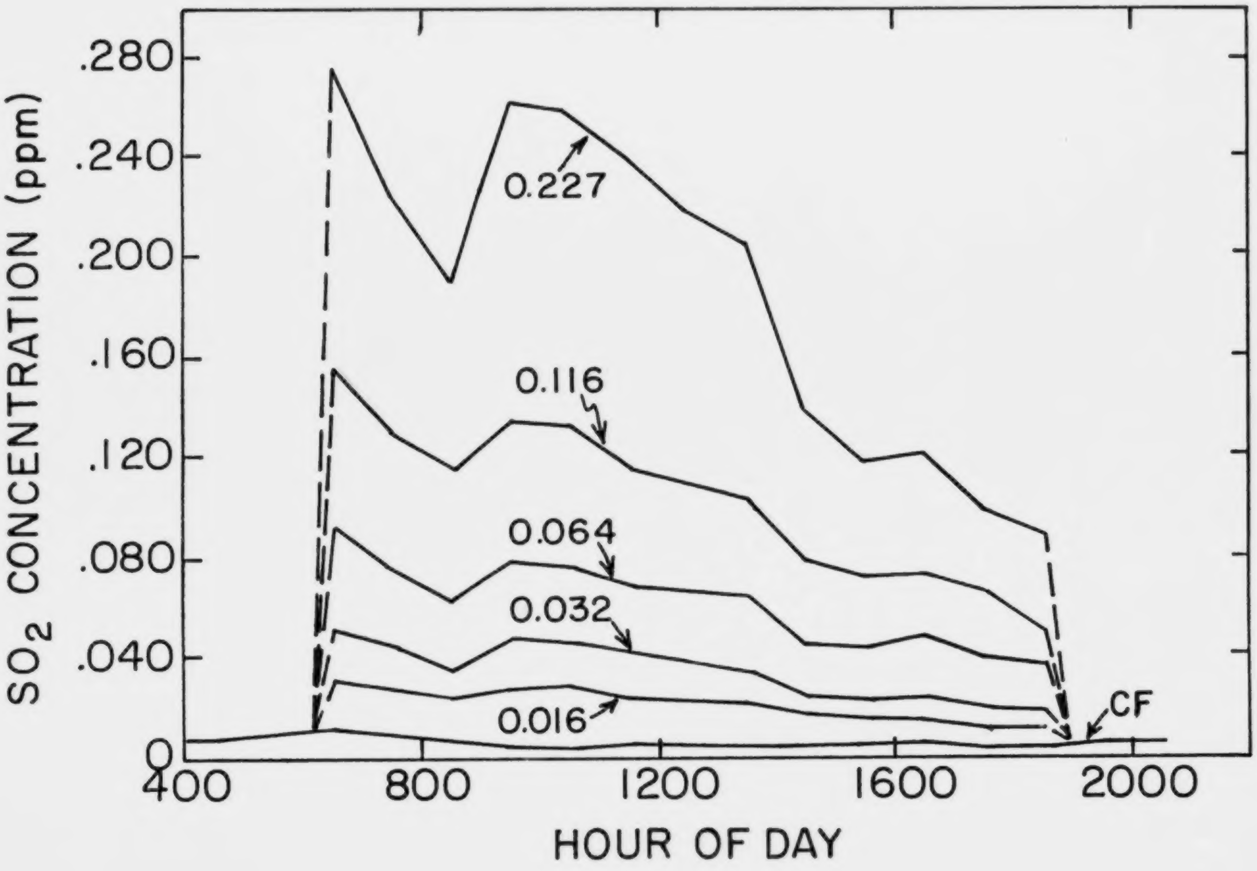

Figure 4.3.1.5. Diurnal curves of seasonal mean concentrations for SO_2 treatments at Tracy, California, in 1981.

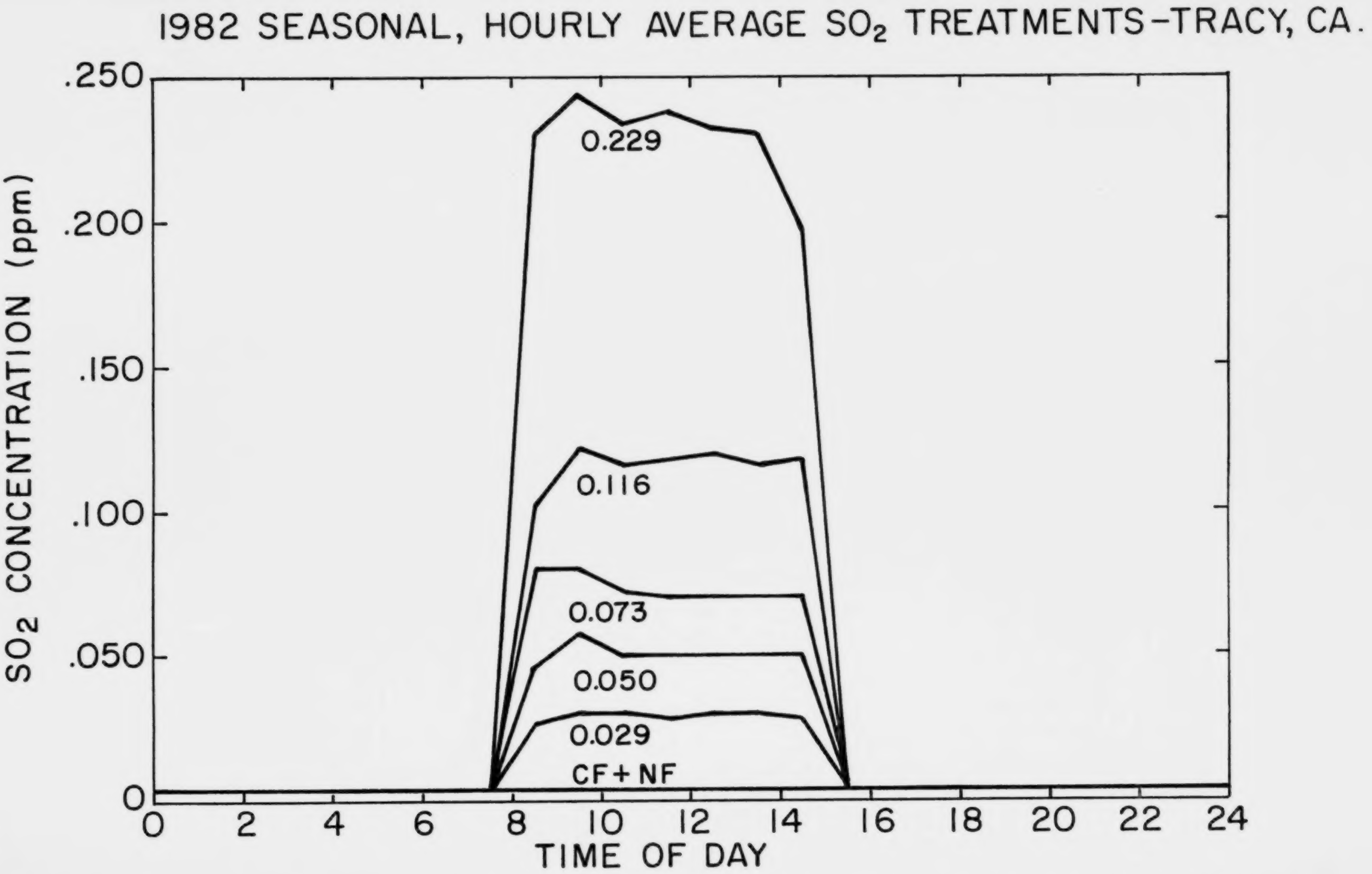

Figure 4.3.1.6. Diurnal curves of seasonal mean hourly SO_2 concentrations for SO_2 treatments in 1981 at Tracy, California.

TABLE 4.3.1.7. TOTAL TOMATO FRUIT FRESH WEIGHT (tons/ha) FROM 1981 HARVEST, TRACY, CALIFORNIA.

	O_3 (ppm)†				
SO_2 (ppm)†	0.012	0.038	0.062	0.085	0.102
0.006	61.8**	62.4	65.5	55.2	55.2
0.016	73.0	52.8**	61.4	48.9	44.4
0.032	71.4	65.4	69.1	56.4	45.8
0.064	51.1	53.4	52.1	49.9	42.7
0.116	67.7	71.2	57.3	56.6	49.7
0.227	43.1	65.9	51.1	51.5	41.7**

* Average of 2 control chambers.

** Estimate.

† Seasonal 7-h average concentration (ppm) (0800-1500 PST).

TABLE 4.3.1.8. TOTAL TOMATO FRUIT FRESH WEIGHT (tons/ha) FROM 1982 EXPERIMENT, TRACY, CALIFORNIA.

	O_3 (ppm)†				
SO_2 (ppm)†	0.012	0.038	0.062	0.085	0.102
0.002	62.6*	58.9	49.3	58.7	46.6
0.029	71.2	56.7	72.8	58.3	42.7
0.050	55.8	54.4	50.1	50.5	45.8
0.073	59.5**	55.6	54.4	54.8	48.5
0.116	54.0	60.7	42.7	43.1	53.4
0.229	54.0	55.4	41.5	35.2	46.6

* Average of 2 control chambers.

** Estimate.

† Seasonal 7-h average concentration (ppm) (0800-1500 PST).

TABLE 4.3.1.9. ANALYSIS OF VARIANCE OF TOTAL TOMATO FRUIT FRESH WEIGHT FROM OPEN-TOP CHAMBERS AT TRACY, CALIFORNIA, 1981-1982.

Source	df	SS	MS	F
Year	1	42.6727	42.6727	4.73*
O_3	4	391.3290	97.8322	10.84**
SO_2	5	177.9453	35.5891	3.94*
Year x O_3	4	32.0357	8.0089	0.89
Year x SO_2	5	142.1913	28.4383	3.15*
O_3 x SO_2	20	266.8930	13.3437	1.48
Error	17	153.3903	9.0230	
Total	56†			

* Significant at 5% level.

** Significant at 1% level.

† Degrees of freedom adjusted for plot estimates.

TABLE 4.3.1.10. REGRESSION EQUATIONS AND STATISTICS FOR YIELDS OF TOMATO FRUIT FRESH WEIGHT OF FIELD-GROWN TOMATOES AND O_3 AND SO_2 CONCENTRATIONS AT TRACY, CALIFORNIA, 1981-1982.

Year	Regression Equation	R^2	F
1981	$Y = (-38.85) \times SO_2) - (1702.59 \times O_3^2) + 67.08$	0.67	17.23
1981	$Y = (-38.63) \times SO_2) - (4735.94 \times O_3^2) + 63.81$	0.46	11.33

Y = yield (ton/ha).

SO_2 = SO_2 seasonal 7-h average concentration (ppm).

O_3 = O_3 seasonal 7-h average concentration (ppm).

Although the analysis of variance had shown a significant year x SO_2 interaction, SO_2 regression coefficients for the two years were nearly identical, indicating that tomatoes responded similarly to SO_2 in both years, as shown in Figure 4.3.1.7. Yield reductions due to SO_2 occurred only at the highest doses, indicating that field-grown tomatoes are relatively resistant to SO_2. In contrast, the coefficient for O_3 in the 1982 regression equation was 2.8 times higher than in 1981, indicating that the plants responded more strongly to O_3 in 1982 than in the previous year. Yearly responses to O_3 are shown in Figure 4.3.1.8.

Yield Reduction. A seasonal average O_3 concentration of 0.05 ppm produced a 6% reduction in yield for 1981, which was a typical year climatically, but the same concentration procued a 19% reduction in yield in 1982, which was a cool, moist year. Ambient O_3 concentrations reduced tomato yield 3% in 1981, but in 1982 essentially the same ambient O_3 concentrations reduced yield of tomatoes by 6% (Table 4.3.1.11). This contrast in plant response to O_3 between the two years may be attributable to seasonal differences in growing conditions in the Central Valley. 1981 had a typically hot, dry climate during the summer growing season (NOAA Climatological Summary, 1981). Under these conditions, evaporative demand is high, and stomata may close during the hottest part of the afternoon, when O_3 is normally present in highest concentrations. In contrast, 1982 was unusually cool, and cloudy conditions were more prevalent than normal. Plants may be more susceptible to O_3 injury under these conditions because stomata may remain open for longer periods of time during the day and between irrigations.

4.3.1.4 Conclusions

A two-year study of the dose-response to O_3 and SO_2 of commercially grown tomatoes in open-top chambers was completed in 1982. Statistical analyses showed that both O_3 and SO_2 were significant in reducing yield, but there was no significant interaction between the two pollutants. Stepwise multiple regresion showed that the dose-response could be represented as the additive effect of the square of O_3 concentration plus the SO_2 concentration. In two years, the regression coefficients were about the same for SO_2, but increased by a factor of 2.8 for O_3 during the cool, moist year of 1982. That only these additive terms were significant in both 1981 and 1982 gives consistency to the dose-response functions.

Ambient O_3 levels (0.033 ppm averaged over a 7-h daytime period) produced only 3% yield loss in typical weather conditions but 6% yield loss in the atypical cool, moist year of 1982. An O_3 concentration of 0.050 ppm could produce a 6% loss in a typical year like 1981, but 19% reduction in yield in a year like 1982. The tomato crop was not particularly susceptible to SO_2 exposure, requiring 0.17 ppm for 10% yield reduction in both years, if no O_3 were present. The additive effect, however, shows that lesser amounts of SO_2 would increase the yield reduction already occurring due to O_3; for example, in 1982, 0.032 ppm SO_2 added to 0.033 ppm O_3 produced 10% yield reduction.

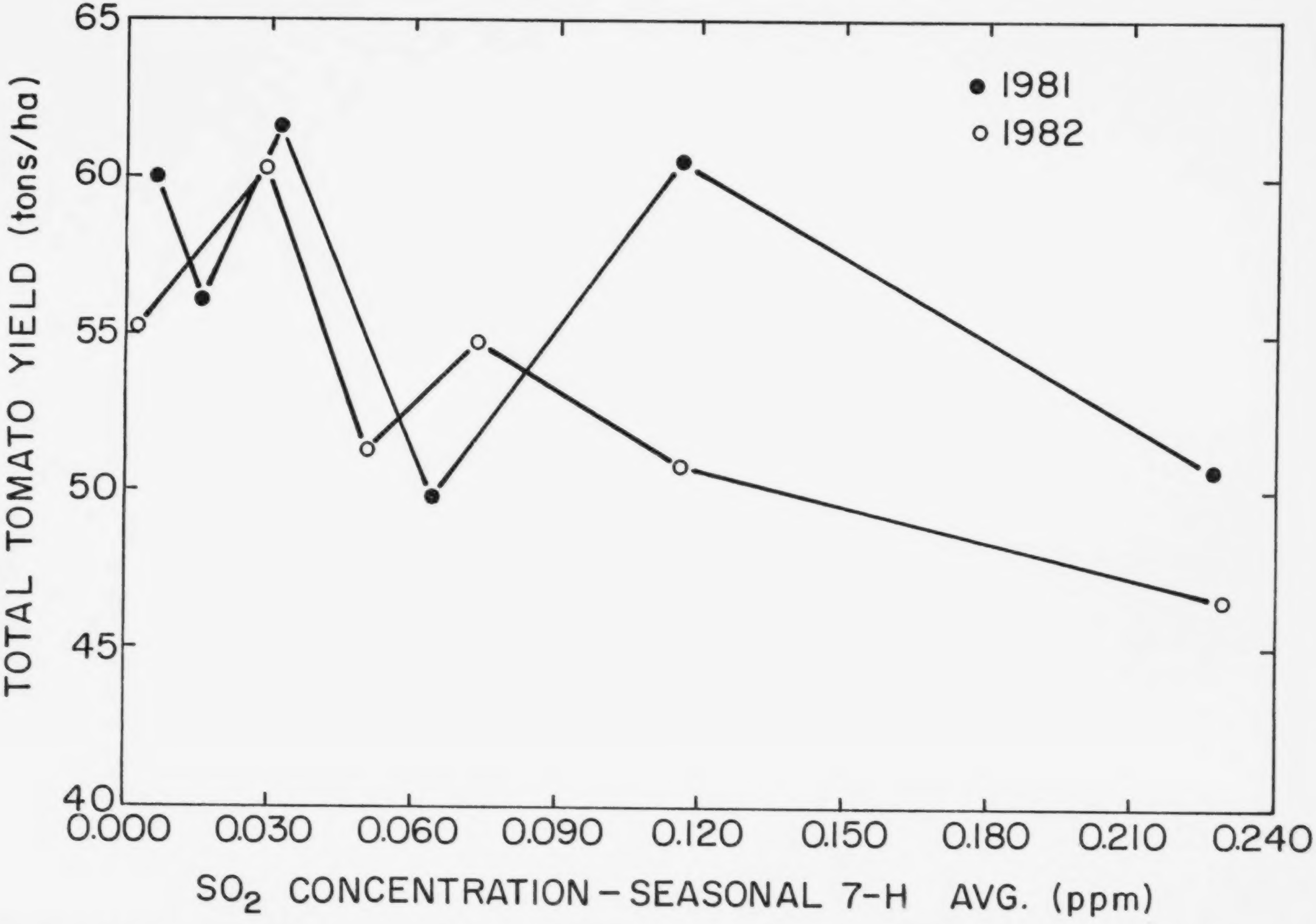

Figure 4.3.1.7. Dose-response of yield of field-grown tomatoes to SO_2 measured across O_3 treatments at Tracy, California, 1981, 1982.

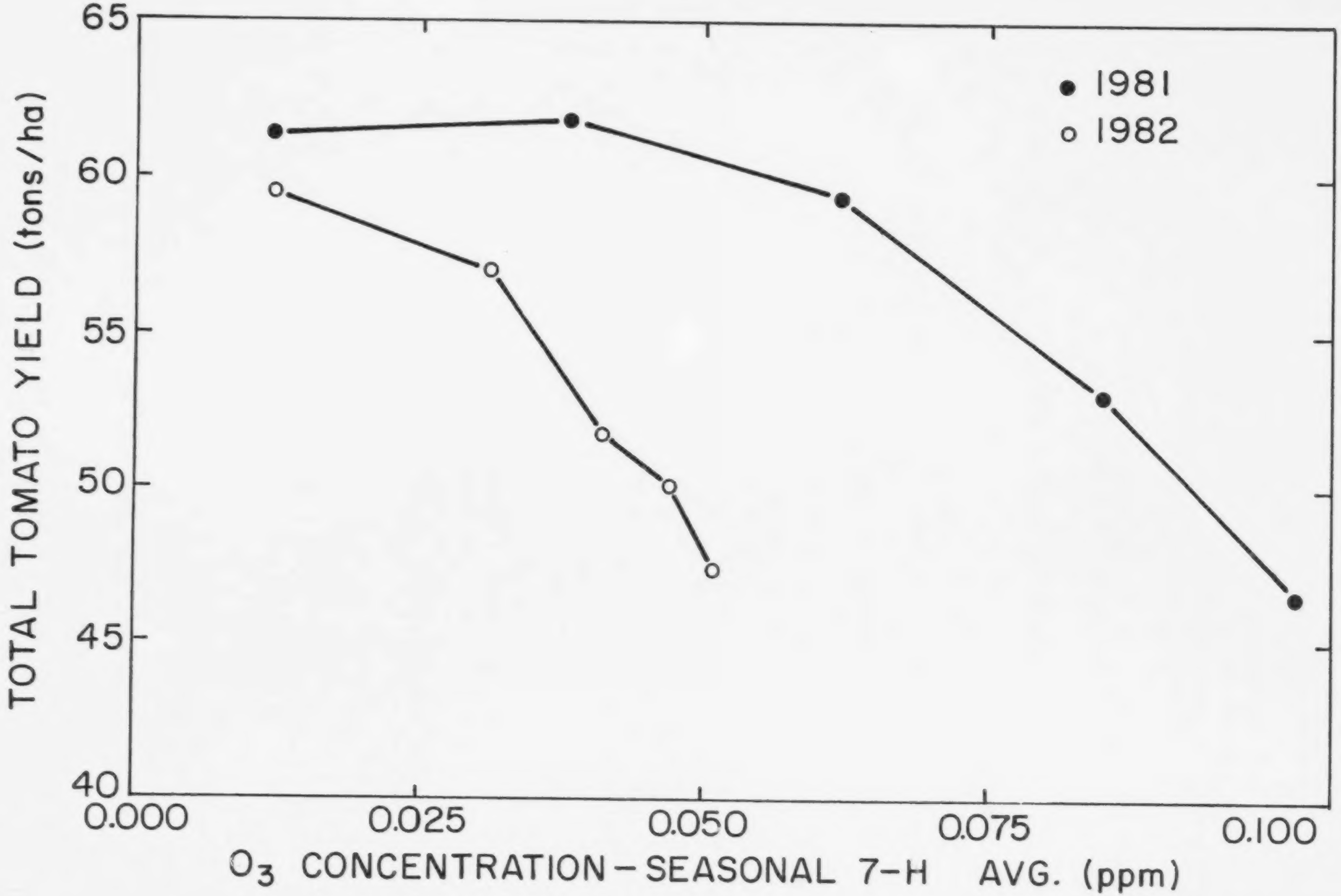

Figure 4.3.1.8. Dose-response of yield of field-grown tomatoes to O_3 measured across SO_2 treatments at Tracy, California, 1981, 1982.

TABLE 4.3.1.11. REDUCTIONS IN YIELD OF TOTAL FRESH WEIGHT OF TOMATO BY VARIOUS COMBINATIONS OF O_3 AND SO_2, BASED ON REGRESSION MODELS (Table 4.3.1.10).*

Year	Average O_3 (ppm)	Average SO_2 (ppm)	Yield Reduction (%)
1981	0.033	0	3
	0.050	0	6
	0.100	0	25
	0.033	0.120	10
	0	0.170	10
1982	0.033	0	6
	0.050	0	19
	0.033	0.032	10
	0	0.170	10

* For both 1981 and 1982, ambient O_3 was 0.033 ± 0.002 ppm and ambient SO_2 was 0.007 ± 0.003 ppm.

4.3.2 Response of Cotton to Chronic Doses of O_3 and SO_2 (SERCLAP)*

4.3.2.1 Introduction

This study was designed to provide information on the effects of chronic doses of O_3 and SO_2 on injury, growth, and yield of cotton grown in the field. another objective was to determine whether the presence of either pollutant would change the response of cotton plants to exposure to the other. Standard NCLAN protocols were used to establish five chronic doses of O_3 and four chronic doses of SO_2, singly and in mixtures, in 20 standard open-top chambers. Preliminary testing was done to determine whether a truncated cone (frustum) addition to the top of open-top chambers would alter plant response to O_3. The five O_3 doses without SO_2 added were used in both standard chambers and in those with frusta added.

4.3.2.2 Materials and Methods

Cultural. The experiment was performed in a field of Norfolk loamy sand (fine-loamy, siliceous, thermic, Typic paleudult) which had previously been fertilized according to soil test recommendations. Details of fertilizer and herbicide applications are shown in Table 4.3.2.1.

Cotton (*Gossypium hirsutum* L. cv. 'Stoneville 213') was plantd with a two-row planter in rows spaced 1 meter on 20 May 1982. Plants emerged on 24 May and 27 3-m^2 plots were selected based on plant density (enough emergence to allow thinning to a uniform density in all plots) and appearance of soil.

On 31 May, open-top chamber frames were installed on 25 plots. Two plots were not enclosed by chambers. For each plot, plants were thinned on 11 June to 3-4 plants per 30 cm of row. This resulted in a stand of 9 to 11 plants in each of two 1-m sections for each of two rows within the chambers. There was approximately 50 cm at the ends of each row where no plant measurements were taken. Soil tensiometers (Irrometer Company, Riverside, California) were installed in each plot at depths of 30 and 45 cm on 21 June. Tensiometer readings were recorded three times weekly and plots were irrigated using drip tubing for a 6-m length of four rows (the two plot rows and two border rows). Plots were irrigated with 2.5 cm of water when readings for 40 to 50% of the tensiometers at 30 cm exceeded 50% of scale. The seasonal climate was normal with 47 cm of rain. Total irrigation was 17 cm. Insects and mites were effectively controlled in the treatment plots and in companion plots with applications of dimethoate (Cygon), dicofol, and permethrin as shown in Table 4.3.2.1. Three aerial applications of azinphosmethyl (Guthion) were made which partially controlled an infestation of boll weevils in the non-plot cotton.

Pollutant Treatment. Clear polyvinyl chloride film panels were installed and chamber fans were activated on 7 June. Fans were run from 0600 to 2200 h EDT for the rest of the season. Five levels of O_3 and four levels of SO_2 (20 possible combinations) were randomly assigned and established in 20 chambers using methods for dispensing and monitoring described previously. The five O_3

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* Allen S. Heagle, Marla J. S. Lee, Fred L. Mowry, R. B. Philbeck, W. W. Heck, J. O. Rawlings, and V. M. Lesser, Raleigh, North Carolina.

TABLE 4.3.2.1. DATES FOR IMPORTANT EVENTS DURING 1982 STUDIES TO DETERMINE THE EFFECT OF CHRONIC DOSES OF O_3 AND SO_2 ON INJURY, GROWTH, AND YIELD OF 'STONEVILLE 213' COTTON AT RALEIGH, NORTH CAROLINA.

Month	Day	Event
May	10	Fertilizer applied (14-0-14, N-P-K) 715 lb/acre
	19	Treflan applied (4 lb/gal, 1/8 gal/acre)
	20	Planted cotton 'Stoneville 213'
	20	Cotoran applied (80 WP, 1¼ lb/acre)
	24	Plants emerged
June	7	Panels installed on chambers, fans on
	9	Began O_3 dispensing
	11	Began SO_2 dispensing
	21	Irrometers installed
	25	Soil sampled from all plots
	11	Dimethoate (Cygon) applied (23.4% EC 6 ml/l)
September	2	Dimethoate applied (2-E, 2/3 pint/acre)
July	27	Dicofol (16 oz/100 gal) and Permethrin (1 pint/100 gal) applied
August	3	Dicofol (18 oz/100 gal) and Permethrin (1.14 pint/100 gal) applied
August	12	Cyhexatin (28.4 g/100 gal) and Permethrin (1.14 pint/100 gal) applied
	18	Cyhexatin (28.4 g/100 gal) and Permethrin (1.14 pint/100 gal applied)
	27	Permethrin (1.14 pint/100 gal) applied
September	17	Guthion (azinphosmethyl) applied (1 pint/acre)
	25	Guthion (1 pint/acre) applied
October	5	Guthion (1 pint/acre) applied)
July	16	Foliar injury estimated, bolls counted
August	24	Foliar injury estimated, bolls counted
September	24	Foliar injury estimated, bolls counted
September	27	cotton picked in treatment plots
October	5,12,20,27	cotton picked in treatment plots
September	28	cotton picked in companion plots
October	5,15,20,28	cotton picked in companion plots
October	5	Last day of dispensing O_3 and SO_2
	6	All chambers receiving NF air
	27	Chamber fans turned off
November	2	Soil sampled from all plots

treatments consisted of charcoal-filtered air (CF) and five nonfiltered air (NF) treatments (particle filter only). For each NF treatment (NF-1, NF-2, NF-3, and NF-4) a different, but constant, amount of O_3 (resulting in concentrations of approximately 0.00, 0.02, 0.04, and 0.06 ppm, respectively, above ambient O_3) was added for 7-h/day (1000 to 1700 hrs EDT) producing a series of 7-h O_3 curves. Dispensing of O_3 began on 9 June, 16 days after plants emerged, when first foliar leaves were beginning to expand. O_3 was added daily until 5 October (119 days) when all leaves of plants in all but the CF and NF-1 treatments were chlorotic or necrotic. However, O_3 was not added during periods of rain(a total of 38.5 exposure hours during the season) or when dispensing systems malfunctioned (a total of 52.5 exposure hours during the season).

The SO_2 treatments consisted of exposure to CF air (S-0), or NF air to which three levels of SO_2 (S-1, S-2, and S-3) were added for 4-h/day (1000 to 1400 EDT). Dispensing of SO_2 began on 11 June and continued until 5 October (117 days) except during periods of rain (a total of 24.5 exposure hr during the season) or system malfunction (a total of 8.8 exposure hours during the season). Dispensing flow rates were measured directly at each O_3 and SO_2 chamber inlet port three times each week using a calibrated rotameter to insure accurate dispensing flow rates.

In addition to the treatments already listed, a preliminary test of the effects of frusta (truncated cones) on plant response to O_3 was performed. Five of the original 27 plots were randomly assigned to chambers equipped with frusta. These were used to expose plants to the five O_3 treatments with no added SO_2.

Response Measurements. Foliar injury was estimated as the percent chlorosis and necrosis in 5% increments (0-100%) for each leaf arising from the main stem of four plants (one for each 1-m of row per plot). The same plants were used for counting squares and bolls per axillary branch. Injury estimates and square and boll counts were made on 16 July, 24 August, and 24 September using the same plants at each date.

Cotton from each 1-m of row was hand picked on 28 September, 5, 12, 20, and 27 October). In an attempt to simulate mechanical harvest, loose cotton from opened bolls was picked. The cotton (unginned) was weighed after each harvest at field moisture content. At the final harvest, the number and weight of unopened bolls and those partially opened but not yet harvestable were determined for each 1-m of row. After harvest, a 500-g sample of raw cotton from each plot was ginned (seeds were mechanically separated from lint) and the percentage of lint and seed were recorded separately. Seed and lint samples were analyzed for quality factors used to establish market price.

Two "companion" plots outside each treatment plot were used to measure effects of edaphic variability across the field on yield for possible covariance analysis. Each companion plot was a 2-m row located 1.2-m east or 1.2-m west of the fiter box of each chamber. All cultural practices for companion plots were the same as those for the main plots. Cotton from the companion plots was picked and weighed on 28 September, 5, 15, 20, and 28 October.

Statistical Analyses. The analysis of data for unginned cotton weight and number of harvested bolls took place in several stages. The first was an analysis of the unginned cotton weight data from the companion plots to determine the nature of any variation within the field. Fitted response surface values for each treatment plot were obtained as well as averaged values (mean of 2 companion plot rows) for each treatment plot. The fitted values were obtained by regressing the companion plot yield on the field position coordinates of the companion plots in order to determine a polynomial response surface for the field. The polynomial response surface was then used to determine predicted performance levels at each treatment plot site.

The second stage of the analysis involved an analysis of variance to test the effect of quadrant positions within treatment plots. The treatment sums of squares was partitioned into that due to O_3 levels, that due to SO_2 levels, and that due to the interaction of O_3 and SO_2. The key findings of this analysis were that quadrant effects were significant, but that there was no treatment by quadrant interaction. Therefore, the third stage of the analysis involved the average over the four quadrants of the treatment plots. The analysis consisted of O_3 levels, O_3 by top (frustum or no frustum) interaction, SO_2 levels, O_3 by SO_2 interaction, and experimental error. Analyses in this form were used to assess the importance of the covariate data obtained from the companion plots. Neither the fitted values or averaged value of the companion plot data accounted for a significant part of the field variation. Consequently, the final dose-response models were fit without covariates being involved. The fourth phase of the analysis involved fitting dose-response models. The dose-response models fit were bivariate, including O_3 levels and SO_2 levels using the seasonal 7- or 4-h mean concentrations of O_3 and SO_2 shown in Table 4.3.2.2. In all cases, significance of a particular polynomial term mandated that all lower-order terms contained in that model will be retained; for example, if $O_3 \times SO_2$ was a significant product term, then O_3 and SO_2 linears were kept in the model.

4.3.2.3 Results

Pollutant doses. The mean seasonal O_3 concentration (mean 7-h/day O_3 concentration during the period of O_3 dispensing) in ambient air (AA) was 0.953 ppm. The mean seasonal 7-h/day O_3 concentrations for no-frustum chambers for the CF, NF-1, NF-2, NF-3, and NF-4 treatments were 0.026, 0.058, 0.072, 0.085, and 0.104 ppm, respectively (Table 4.3.2.2). The respective seasonal O_3 values for the chambers with frusta were 0.013, 0.058, 0.067, 0.087, and 0.095 ppm. The CF value shows that the frustum decreased incursion of ambient O_3 by 50%. Thus, for each O_3 level, less O_3 was added to chambers with frusta than was added to chambers without frusta. The daily 7- and 24-h mean O_3 concentrations in AA from 9 June through 10 October are shown in Figure 4.3.2.1. The mean seasonal dirunal fluctuations in O_3 concentration for AA and for the chamber treatments for the same period are shown in Figure 4.3.2.2.

The mean seasonal SO_2 concentrations (mean 4-h/day concentrations during the period of SO_2 dispensing) for the S-0, S-1, S-2, and S-3 treatments were 0.000, 0.029, 0.097, and 0.350 ppm, respectively (Table 4.3.2.1). Because SO_2 was not detected in ambient air during continuous monitoring, the zero values and time intervals for periods when dispensing did not occur were not included

TABLE 4.3.2.2. O_3 AND SO_2 CONCENTRATIONS FOR STUDIES TO DETERMINE THE EFFECT OF DAILY EXPOURES ON STONEVILLE 213 COTTON AT RALEIGH, NORTH CAROLINA.

	O_3					
	7 h/day Values (ppm)			1 h/day Peak Values (ppm)		
Treatment	Seasonal Mean	Highest	Second Highest	Seasonal Mean	Highest	Second Highest
CF	0.026	0.056	0.041	0.033	0.055	0.051
NF	0.058	0.076	0.076	0.068	0.108	0.107
NF + 20	0.072	0.097	0.092	0.085	0.129	0.112
NF + 40	0.085	0.117	0.111	0.100	0.137	0.131
NF + 60	0.104	0.147	0.132	0.123	0.172	0.163
AA	0.053	0.075	0.074	0.063	0.105	0.094

	SO_2					
	4 h/day Values (ppm)			1 h/day Peak Values (ppm)		
Treatment	Seasonal Mean	Highest	Second Highest	Seasonal Mean	Highest	Second Highest
S-0	0	0	0	0	0	0
S-1	0.020	0.053	0.052	0.030	0.115	0.111
S-2	0.097	0.145	0.138	0.123	0.672	0.257
S-3	0.350	0.556	0.518	0.421	0.656	0.627

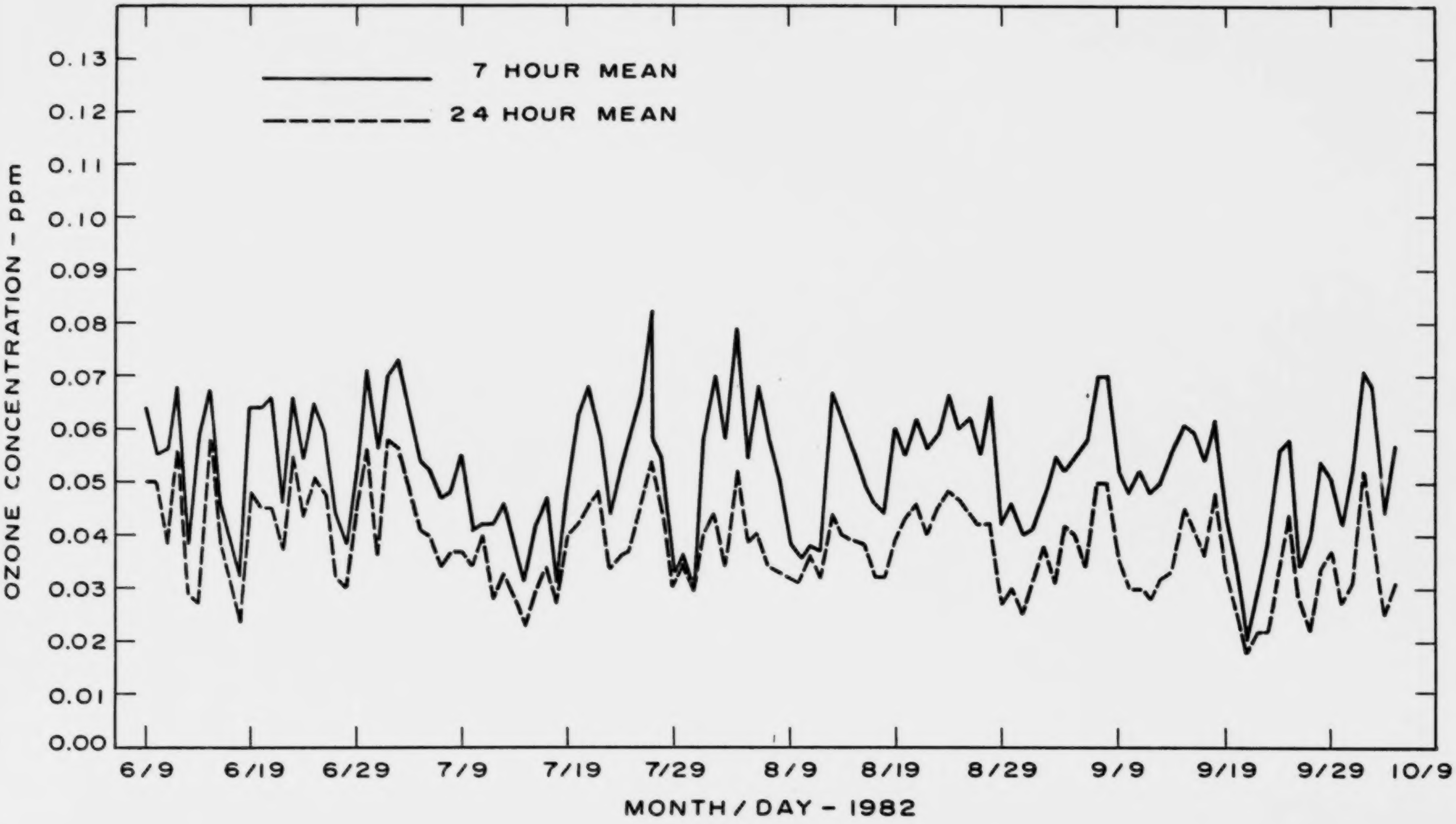

Figure 4.3.2.1. Daily 7-h (1000 to 1700 EDT) and 24-h mean O_3 concentrations during the period of exposures for the 1982 cotton experiment at Raleigh, North Carolina.

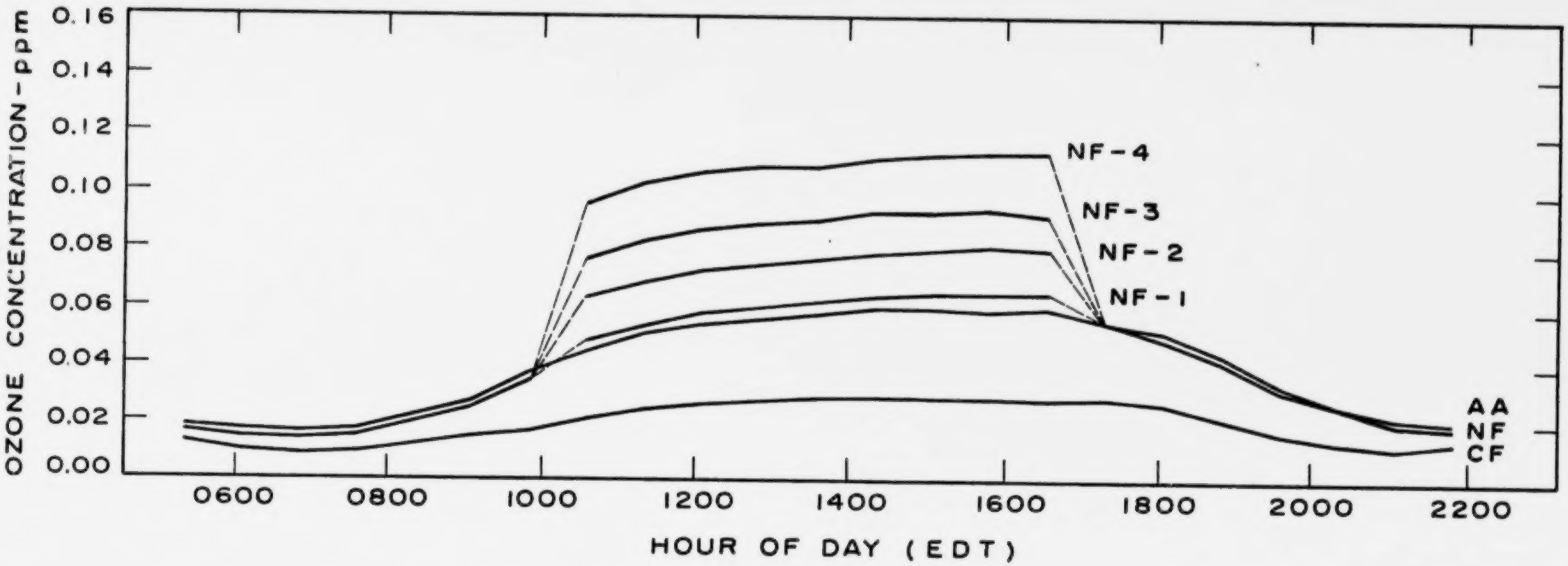

Figure 4.3.2.2. Seasonal (9 June to 5 October) diurnal fluctuation in concentration for the various O_3 treatments in the 1982 cotton experiment at Raleigh, North Carolina. CF = charcoal-filtered air; NF = the common concentration for all nonfiltered-air chambers during the period of each day when O_3 was not added; NF-1, 2, 3, and 4 = concentrations for nonfiltered-air chambers during the 7-h dispensing periods.

in calculating the seasonal SO_2 means. The amounts of SO_2 added to each chamber treatment were constant throughout the season. However, variation in ambient wind velocity effectively created different concentrations within the chambers due to dilution by ambient air ingress through the open tops. The daily fluctuations in 4-h mean SO_2 concentrations and mean seasonal 4-h SO_2 concentration curves are shown in Figures 4.3.2.3 and 4.2.3.4, respectively.

Foliar Injury. There were significant O_3 effects on foliar injury, but no significant frustum effects, SO_2 effect, or $O_3 \times SO_2$ interactions occurred. The effects of O_3 on foliar injury (combined data for all SO_2 levels) for each of three injury readings are shown in Table 4.3.2.3.

Yield. For all treatments, the mean percentage of fiber and seed (by weight) in unginned cotton was 40.3 and 59.7, respectively. Values for individual treatments varied by less than 1% of the means. Thus, the amount of raw (unginned) cotton will be considered as the yield measure for subsequent discussion. The analyses for seed cotton weight and boll numbers showed significant treatment effects and sampling position effects, but there were no position-by-treatment interactions. As the O_3 dose increased, there was a decrease in the number of bolls, raw cotton weight, 100-seed weight, and micronaire reading regardless of the SO_2 dose (Table 4.3.2.3). The regression analyses for boll number and raw cotton weight showed highly significant relationships between the linear and quadratic O_3 doses and yield, but there were no such relationships for SO_2 (Table 4.3.2.4). Interactions between O_3 and SO_2 doses and O_3 doses and chamber configuration were nonsignificant.

Fitting the Weibull model for seed cotton weight and bolls showed no indication of effects caused by SO_2. Therefore, only O_3 was fit to the Weibull model to obtain a crop performance curve.

The Weibull estimates of α, σ, and C for seed cotton and number of cotton bolls are shown in Table 4.3.2.4. The estimated C values of 2.7 (cotton weight) and 3.1 (boll number) indicates a plateau effect, which was also shown in the polynomial model (Figure 4.3.2.5).

4.4 INFLUENCE OF SOIL MOISTURE ON DOSE-RESPONSE RELATIONSHIPS

4.4.1 Influence of Soil Moisture Stress on the Response of Soybeans to $O_3 \times SO_2$ Doses (SERCLAP -- Beltsville, Maryland)*

4.4.1.1 Introduction

The influence of soil moisture stress on the response of crops to O_3 and SO_2 is important in the development of dose-response relationships and the determination of the economic consequences of these pollutants. Data from field studies needed to evaluate the effects of soil moisture stress on plants exposed to ambient levels of pollutants are so deficient that the combined effect of these stresses is essentially unknown. No study of this kind has been conducted in the normally nonirrigated regions of the country. Crops in eastern states are under some moisture stress about 40 percent of the time with considerable variation from season to season. Concern has been expressed

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* H. E. Heggestad, T. J. Gish, J. H. Bennett, and L. W. Douglass.

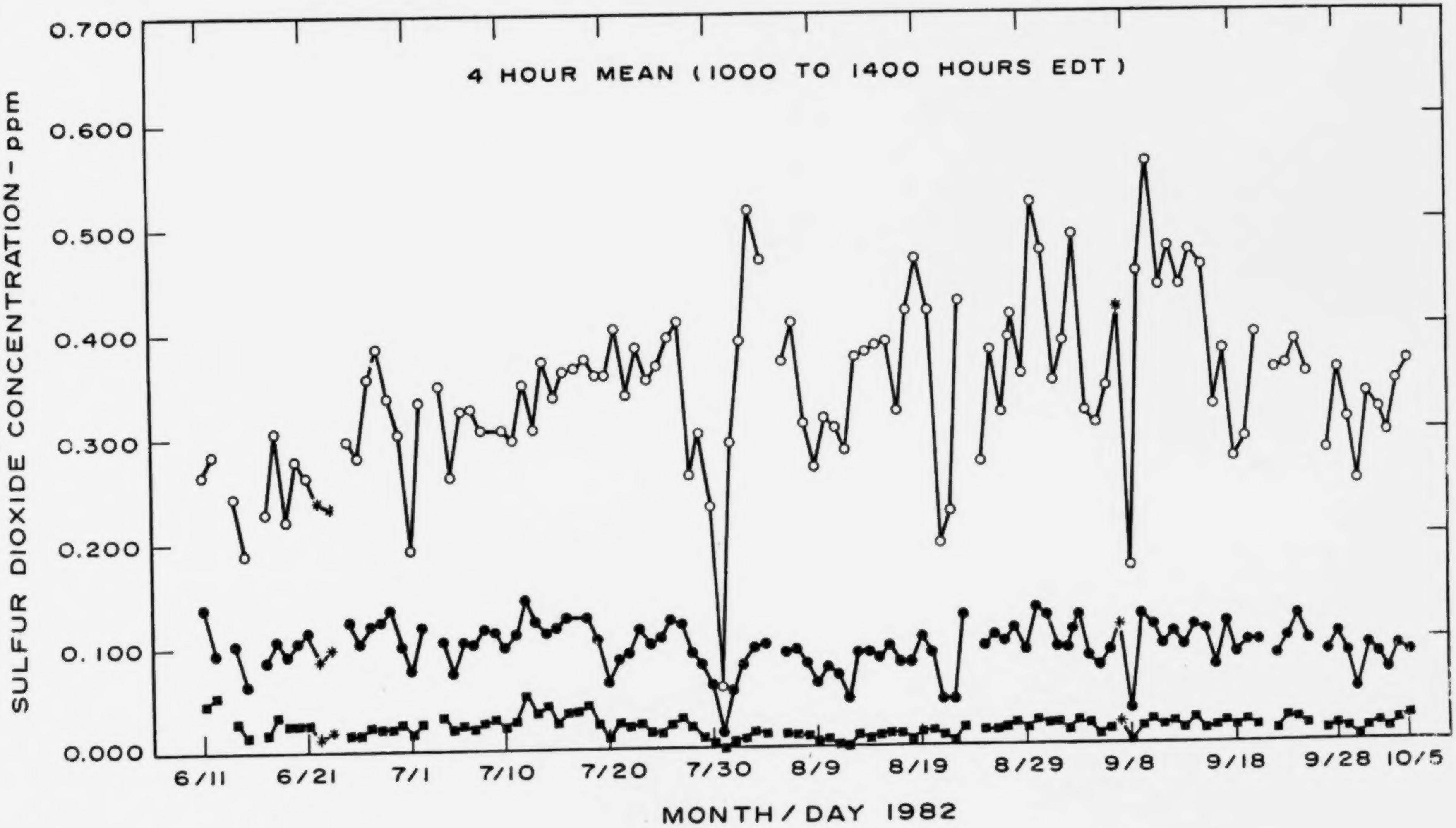

Figure 4.3.2.3. Daily 4-h (1000 to 1400 EDT) mean SO_2 concentrations for the S-1 (■), S-2 (●), and S-3 (o) treatments during the 1982 cotton experiment at Raleigh, North Carolina. * = values for days with less than 4 hours of dispensing. Blanks indicate days with no dispensing. Values are connected only between days of uninterrupted 4-h dispensing periods. Each value is the mean of three chambers.

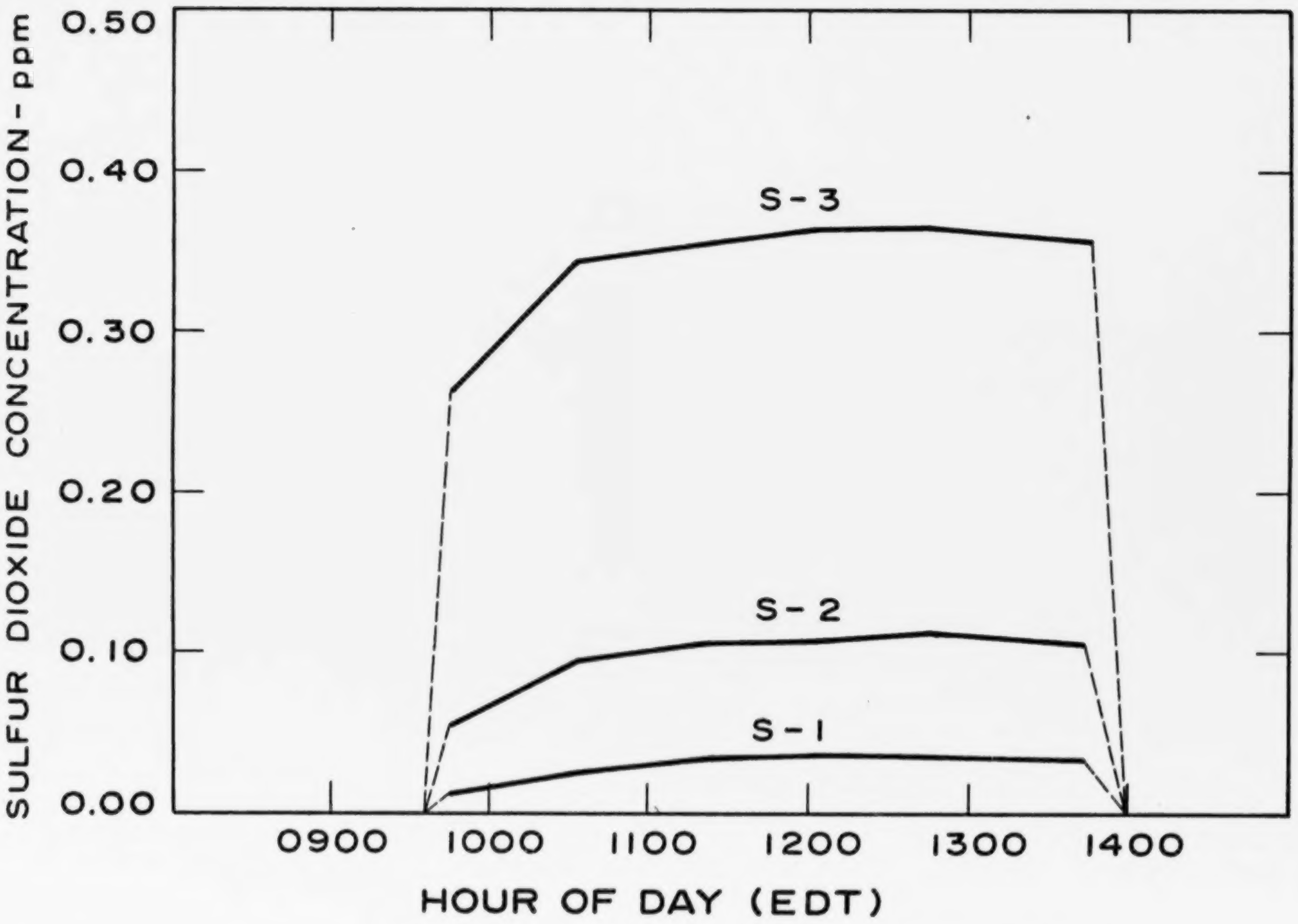

Figure 4.3.2.4. Seasonal (11 June to 5 October) 4-h fluctuation in concentration for the various SO_2 treatments in the 1982 cotton experiment at Raleigh, North Carolina).

TABLE 4.3.2.3. FOLIAR INJURY, NUMBER OF HARVESTED BOLLS, WEIGHT OF UNGINNED (SEED) COTTON, 100-SEED WEIGHT, AND MICRONAIRE RATING OF COTTON (STONEVILLE 213) PLANTS EXPOSED TO MIXTURES OF O_3 AND SO_2 AT RALEIGH, NORTH CAROLINA.

	O_3 Dose	Percentage Foliar Injury			Number of Bolls per Meter	Weight of Raw Cotton per Meter	100-Seed Weight	Micronaire Reading*
		July 16	Aug 24	Sept 24				
Chambers with open tops**	0.026	8	48	79	65	357	10.2	4.9
	0.058	27	66	93	61	316	9.9	4.6
	0.072	37	75	96	57	275	9.9	4.3
	0.085	43	80	98	48	217	9.4	4.2
	0.104	54	85	99	38	161	8.9	3.8
Chambers with frustum tops†	0.013	17	40	87	71	373	10.5	4.6
	0.058	24	58	79	58	300	10.0	4.8
	0.067	37	75	94	58	269	10.2	4.5
	0.087	44	83	91	49	222	9.8	4.2
	0.095	48	82	99	48	199	9.3	4.1

* The micronaire reading is a measure of resistance to air flow of a standard weight of cotton compressed to a standard volume.

** Each value is the mean for four plots (all SO_2 levels combined).

† Each value is the mean for one plot (four 1-meter sections of row) at 0.0 ppm SO_2.

TABLE 4.3.2.4. POLYNOMIAL AND WEIBULL EQUATIONS FOR YIELDS OF STONEVILLE 213 COTTON EXPOSED TO CHRONIC DOSES OF O_3 AND SO_2 IN OPEN-TOP FIELD CHAMBERS AT RALEIGH, NORTH CAROLINA.

	Polynomial*
Seed (unginned) cotton g/l m row	$Y = 372.3 + 53.7x - 20450\ x^2$
Mean # bolls/l m row	$Y = 65.4 + 142.7x - 3875.6\ x^2$
	Weibull[a]
Seed (unginned) cotton weight g/l m row	$Y = 367.3 \exp [(-x/0.111)^{2.71}]$
Mean # bolls/l m row	$Y = 66.6 \exp [(-x/0.125)^{3.13}]$

* Y = predicted yield (weight of cotton, or number of bolls) per meter of row.

x = O_3 concentration (seasonal 7-h/day mean) in ppm.

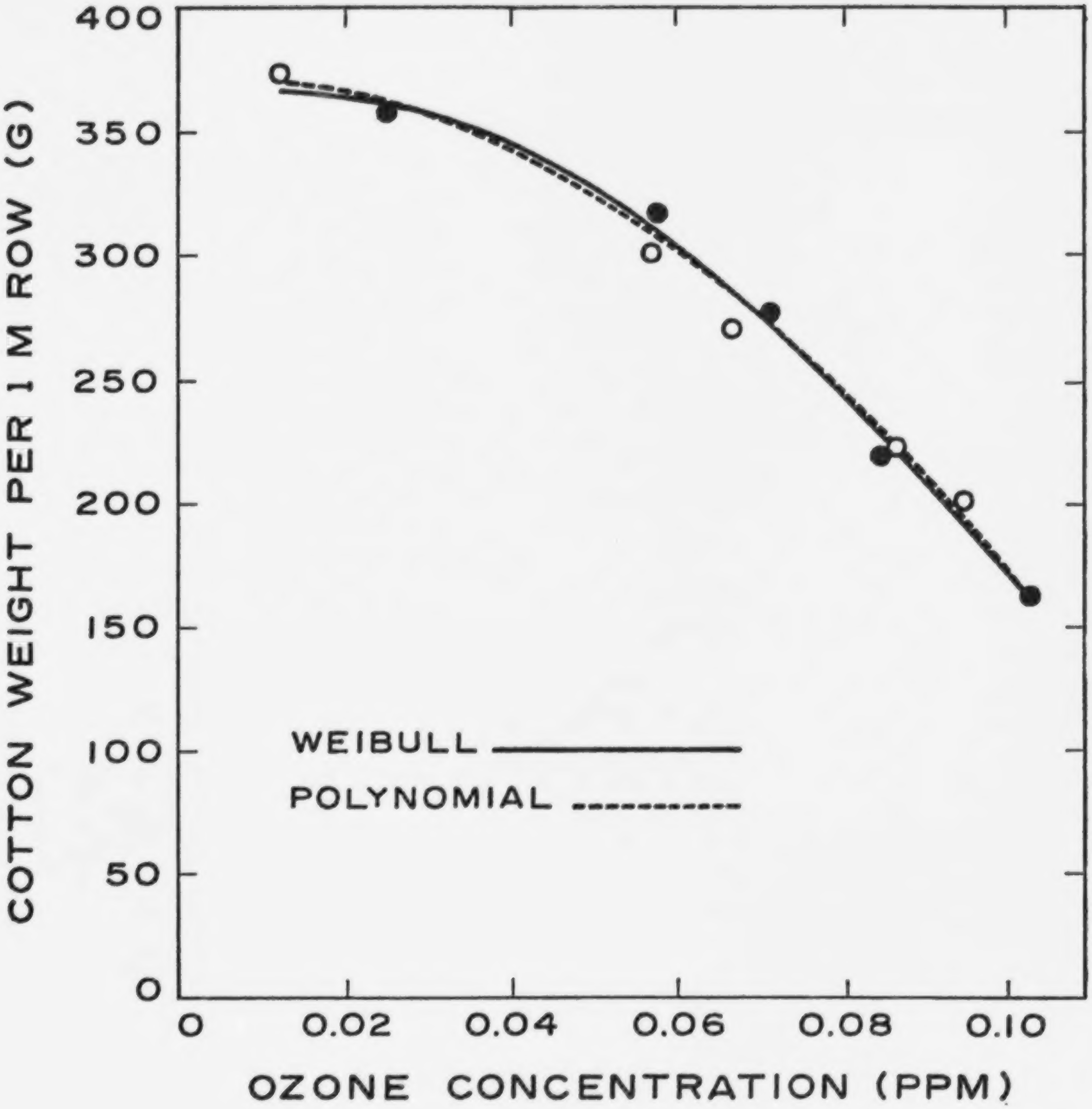

Figure 4.3.2.5. Effects of O_3 on weight of unginned cotton per meter of row as predicted by the polynomial and Weibull analyses for the 1982 cotton experiment at Raleigh, North Carolina. ● = measured values from regular chambers; ○ = measured values from chambers with frusta.

that the NCLAN protocol requiring supplemental irrigation to avoid soil moisture stress in the experiments may result in an overestimation of the effects of O_3 and SO_2. This is because soil moisture stress protects against acute injury induced by a few hours exposure to high concentrations of O_3 and SO_2.

The objective was to assess the impact of moderate soil moisture stress in a field situation on the response of two soybean cultivars when exposed to low concentrations of O_3, SO_2, and their mixtures in the field. In 1982, we exposed soybeans to five O_3 and three SO_2 doses under two soil moisture regimes; i.e., no stress (-0.05 MPa) and moderate soil moisture stress (about -0.44 MPa).

4.4.1.2 Materials and Methods

Cultural. Soybeans, *Glycine max* (L.) Merr. cv. Williams and Forrest, were selected for the study. Williams has been the leading cultivar in the United States for the past 6 years. Forrest was the third leading cultivar in 1981 and it is becoming of increasing importance because of its high tolerance to soybean cyst nematode.

The soil in the plot area is a Codorus silt loam. In spring, the field was graded to fill some low spots and improve the surface drainage. A 5-15-30 N-P-K fertilizer (670 kg/ha) was broadcast and incorporated as the land was prepared for seeding. After seeding, a mixture of two herbicides (Dual-paraquat 1.2 l/ha and Lorox-linuron 1.0 l/ha) were applied on the soil surface.

The seeds were inoculated with *Rhizobium* prior to planting on 26 May 1982. Seeds were planted in rows 0.91 m apart. A few plants were transplanted to improve stand uniformity. The row plots were thinned to a 5 cm spacing as soon as the seedlings were sufficiently established. Plant counts at harvest indicated for both cultivars 20 ± 1 plants per meter or row in all plots.

Insecticides include Plictran (trichlorohexylten hydroxide) for mite control and Guthion (azinphosmethyl) for control of other insects.

Supplemental irrigation was given as needed to avoid moisture stress (-0.05 MPa) in one series of 15 plots and to maintain moderate stress (-0.44 MPa) in another series. Tensiometers (Irrometers) were placed at 25 and 45 cm depths beside the row of Williams and near the center of the row plot. After Williams reached physiologic maturity, the tensiometers were removed and similarly placed near the later maturing cultivar, Forrest.

Soil tensiometers are not capable of measuring water potentials less than -0.09 MPa, consequently soil psychrometers (Wescor, PCT-55-15) were used to monitor the drier soil plots. On 17 August when the psychrometers became available they were placed in each of the 15 dry plots at 25, 45, and 65 cm depths beside the row of Williams and near the chamber center. Tensiometers were also used in the dry plots from 1 July to mid-August and their use was continued in dry plots that were slow to reach the desired water potential. Irrigation of dry plots began in mid-August. By that time plants in some plots were very wilted by midday.

Tensiometers and psychrometers were read each morning and the data used to determine need for irrigation. In the moist series, plots received 0 to 1.25 cm water per day by drip irrigation. In this series the irrigation lines were about 30 cm from the plants on both sides of each row. In the dry series, however, the lines were about 15 cm from the plants. From 0 to 0.25 cm water per day was applied to maintain the desired water potential in the dry series. All irrigation lines had "drips" 50 cm apart. Water requirements decreased as O_3 concentrations increased and it also varied with position in the field. Soil on the west side of the field had less water holding capacity than on the east side. The monthly rain and mean amount of irrigation applied are shown in Table 4.4.1.1.

Beginning 24 August rain was excluded, by using plastic sheeting supported above the chambers. At least 4.4 cm rain was diverted from the plants in the dry series. An additional 2.3 cm was diverted from plots receiving highest O_3 concentrations because of their reduced water use as indicated by soil water potentials especially at the 45 and 65 cm depths.

Exposure treatments. At the two soil moisture potential levels, five concentration of O_3 and three of SO_2 were used in the single replicate 3 x 5 x 2 x 2 factorial set of treatments in a split plot design with cultivars being the subplot treatment (Figure 4.4.1.1). The 30 chamber treatments were randomized within the same field plot area. There were companion plots of the same size as the chamber plots on either side of each chamber plot; i.e., two center rows of a 6-row plot between the chambers. The companion plots were not irrigated. Three companion plots were designated as ambient air plots. In these plots, measurements of growth parameters were made as in chamber plots.

The CF and NF treatments began 27 June and continued until 15 October. The chamber blowers were turned off each night between 2100 and 0500 EST. O_3 additions were NF + 0.03 ppm, NF + 0.06 ppm, and NF + 0.09 ppm. The SO_2 treatments were NF + 0.03 ppm and NF + 0.10 ppm. The higher level of SO_2 was needed to develop a reasonable dose-response function. O_3 was added for 7 h/day between 0900 and 1600 EST. The SO_2 exposures were for 4 h/day between 0900 and 1300 EST. O_3 and SO_2 additions began 8 July and were made on 81 of 86 possible days until 1 October. Rain prevented the exposures on only 5 days. There were no equipment breakdowns during the season which required a delay in the pollutant exposure treatments.

The O_3 was monitored with a Thermo Electron Model (TECO) 49 and a Bendix 8002 O_3 monitor. A Dasibi 1003 PC instrument was used for some O_3 monitoring early in season until the TECO 49 was available. The Dasibi was used primarily for calibration of other instruments. The probes for chamber sampling were placed in the center and kept just above the plant canopy as the plant height increased. A Bendix 8002 O_3 instrument was used to monitor ambient air sampled with a probe located 3 m above the ground on the north side of the field. The SO_2 was monitored with two TECO Model 43 SO_2 analyzers which were calibrated with a TECO Model 143 permeation tube calibrator. Two sets of O_3 and SO_2 monitors were used to sequentially monitor 30 chambers. Each chamber was monitored for O_3 and SO_2 concentration about once every hour. The NCLAN quality assurance plans were followed. The sample lines were checked in two ways. We determined the concentrations in each line on days when oxidants

TABLE 4.4.1.1. RAINFALL AND SUPPLEMENTAL IRRIGATION FOR 15 PLOTS EACH WITH AND WITHOUT SOIL MOISTURE STRESS IN THE SOYBEAN STUDY AT BELTSVILLE, MARYLAND.

	Rainfall		No Moisture Stress (-0.05 MPa)		Moisture Stress (-0.44 MPa)	
Month	Normal**	1982	Water by Irrigation*†	Total Irrigation and Rainfall	Water by Irrigation*†	Total Irrigation and Rainfall
	cm	cm	cm	cm	cm	cm
May	9.7	6.9	0	6.9	0	6.9
June	8.5	14.5	0	14.5	C	14.5
July	10.5	6.7	x, 11.4 (16.0 to 8.4)	18.1	0	6.7
August	11.7	2.7	x, 14.9 (21.8 to 7.9)	17.6	x, 1.6 (2.3 to 1.3)	4.3
September	8.4	6.5	x, 10.1 (16.8 to 5.1)	16.6	x, 3.8 (7.9 to 0.5)	10.3
October	7.6	5.3	x, 0.9 (1.8 to 0)	6.2	x, 0.1 (0.5 to 0)	5.4
Total	56.4	42.6	37.3	79.9	5.5	48.1

* Drip irrigation, each plot (30) irrigated based upon the soil water potential as measured in the morning of each day. Added from 0.25 to 1.5 cm water per day depending upon need.

** Based on recent 30-year record.

† Values in parentheses reveal range of water added for the 15 plots in each soil moisture regime as needed to maintain uniformity in soil water potentials at the 25 to 45 cm depth for the two levels of soil moisture stress. Less irrigation water was required for plots in treatments with the 2 highest concentrations of O_3. Depending in part on field location, the soil water potentials in some plots with 3 lowest O_3 levels reached -0.8 MPa and plants showed severe wilting on sunny days. At that time, it was decided to begin irrigation. When irrigation was started, attempts were made to keep the soil water potentials between -0.4 and -0.5 MPa. Dry plots with CF air and either no SO_2 added, or only the 0.03 ppm level showed less need for irrigation than comparable dry plots receiving NF air.

OZONE, ppm

SO_2, ppm

TREATMENT		CF	NF	NF+0.03	NF+0.06	NF+0.09
0.00	WET	3	1	28	8	22
	DRY	10	4	24	26	23
0.03	WET	14	9	30	12	13
	DRY	19	2	5	21	7
0.12	WET	18	16	6	25	29
	DRY	27	15	11	20	17

Chamber Numbers

21	22	23	24	25	26	27	28	29	30
11	12	13	14	15	16	17	18	19	20
1	2	3	4	5	6	7	8	9	10

Chamber Location

Figure 4.4.1.1. Target O_3 and SO_2 concentrations in the 3 x 5 factorial experiment conducted at two levels of soil moisture and the randomization for the 30 different treatments (chambers) at Beltsville, Maryland.

were 0.08 ppm or higher and quite stable over time. The lines were checked also by the addition of O_3 from the Dasibi calibrator and comparing O_3 values at the chamber with that monitored in the trailer. All sampling lines were within 5% of the Dasibi values as measured in the field; consequently, no adjustments were needed from the values recorded. To minimize losses in long lines, it is important for the lines to be continuously aspirated at a flow of 3 to 4 l per minute.

Plants of Williams were at the beginning reproductive stage (R1) on 8 July when the O_3 and SO_2 exposures began, but Forrest did not reach this stage until 31 July. Williams was harvested before the exposures ended on 1 October, while Forrest was at the R7 physiological maturity stage. There was a killing frost on 18 October. Harvest of Forrest began 20 October and was completed by 3 November.

The O_3 dose was characterized in several ways: (1) daily 7-h and 24-h ambient means (Figure 4.1.1.2); (2) seasonal 7-h means for all treatments with diurnal changes (Figure 4.1.1.3); (3) seasonal and exposure period 7-h means; (4) maximum and second highest hourly mean for each O_3 treatment; (5) maximum and second highest 7-h mean for each treatment; and (6) daily maximum hourly means averaged for the season (Table 4.4.1.2). The O_3 (7-h) and SO_2 (4-h) concentrations arrayed on an individual plot basis for the season and means for each treatment are given in Table 4.4.1.3. The ambient 7- and 24-h mean SO_2 concentrations are presented in Figure 4.4.1.4.

Four plants were permanently tagged in the 2-m length row of each cultivar in each of the chamber and in 3 of the 30 companion plots designated as ambient air plots. Data were taken during the season at 2-week intervals beginning 20 July on plant height, number of nodes, and height from primary node to the first node with a fully green leaf (which is a good measure of leaf senescence). At three intervals about one month apart, the terminal leaflet from a trifoliolate leaf near the top, middle, and bottom of the canopy were sampled from 5 randomly selected plants in each row plot to determine leaf fresh and dry weights and leaf areas. Only the summary data on leaf senescence are included in this report.

Stomatal conductances were measured with a LiCor steady-state autoporometer for a series covering a range of O_3 and SO_2 exposure treatments. Measurements were taken at midday on sunny days and on completely overcast cloudy days. Some measurements were also made of leaf water potentials using a pressure bomb (PMS Instrument, Corvallis, Oregon).

Two-meter row lengths were harvested for each cultivar in each chamber beginning as soon as all the pods on the plants of each cultivar were brown. The 45-cm sections at the end of each plot row were discarded. Williams was harvested beginning 20 September and completed by 29 September. The Forrest harvest began on 20 October and was completed by 3 November. Each of the four tagged plants per row were harvested separately. From each plant, data were taken on plant height, internode numbers, pod numbers, pod weights, and stem weights. Seed weights were determined only on a per plot (2 m/row) basis. The seeds were air dried and the moisture contents were determined for each cultivar and plot. Seed weights were adjusted to obtain a uniform 13 percent moisture content. Seed size was determined based on weight per 100-seed lots. The approved NCLAN Quality Assurance Program was followed.

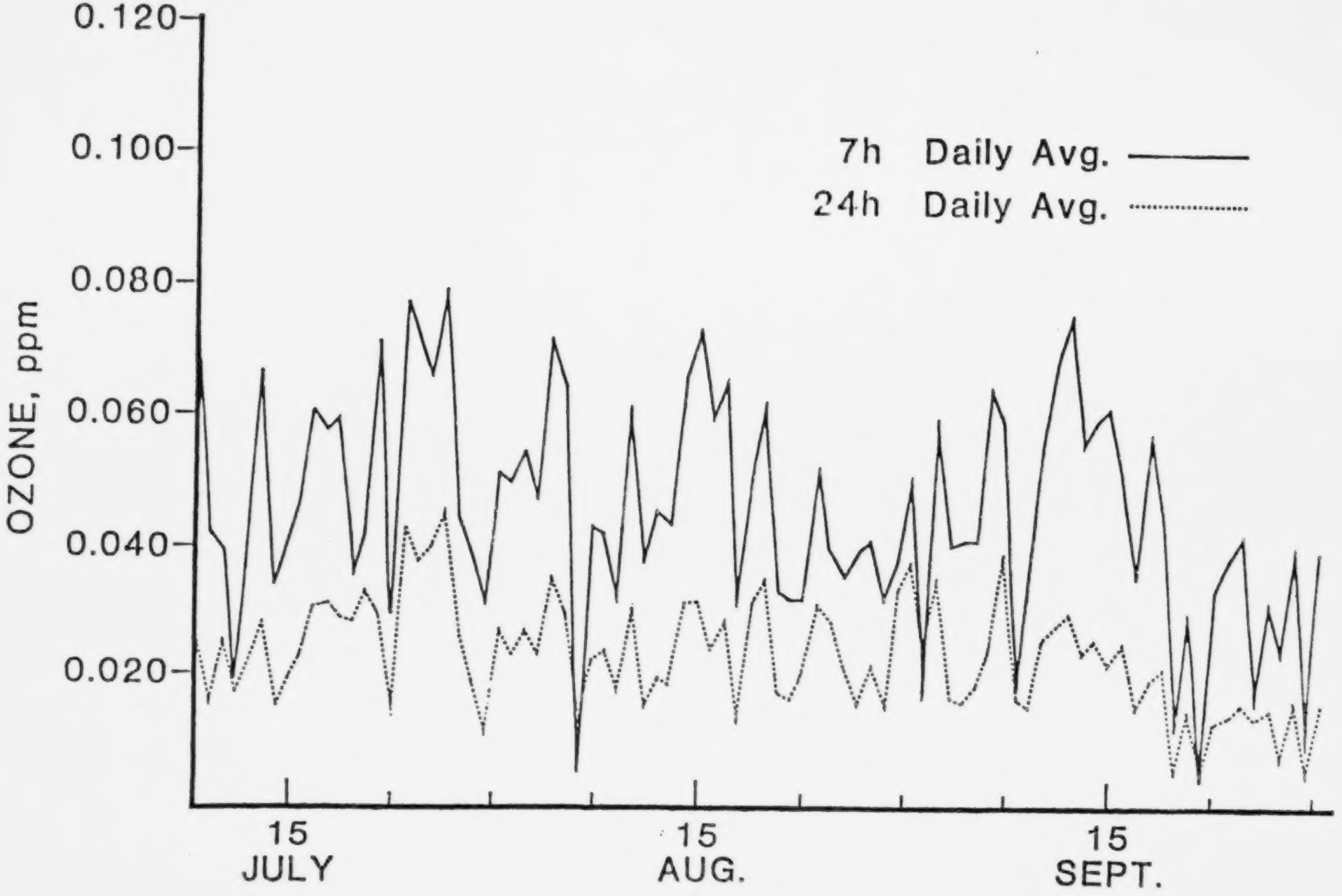

Figure 4.4.1.2. Ambient 7-h (0900-1600 EST) and 24-h O_3 data from 8 July to 10 October sampled at 3 m above ground adjacent to soybean plots at Beltsville, Maryland.

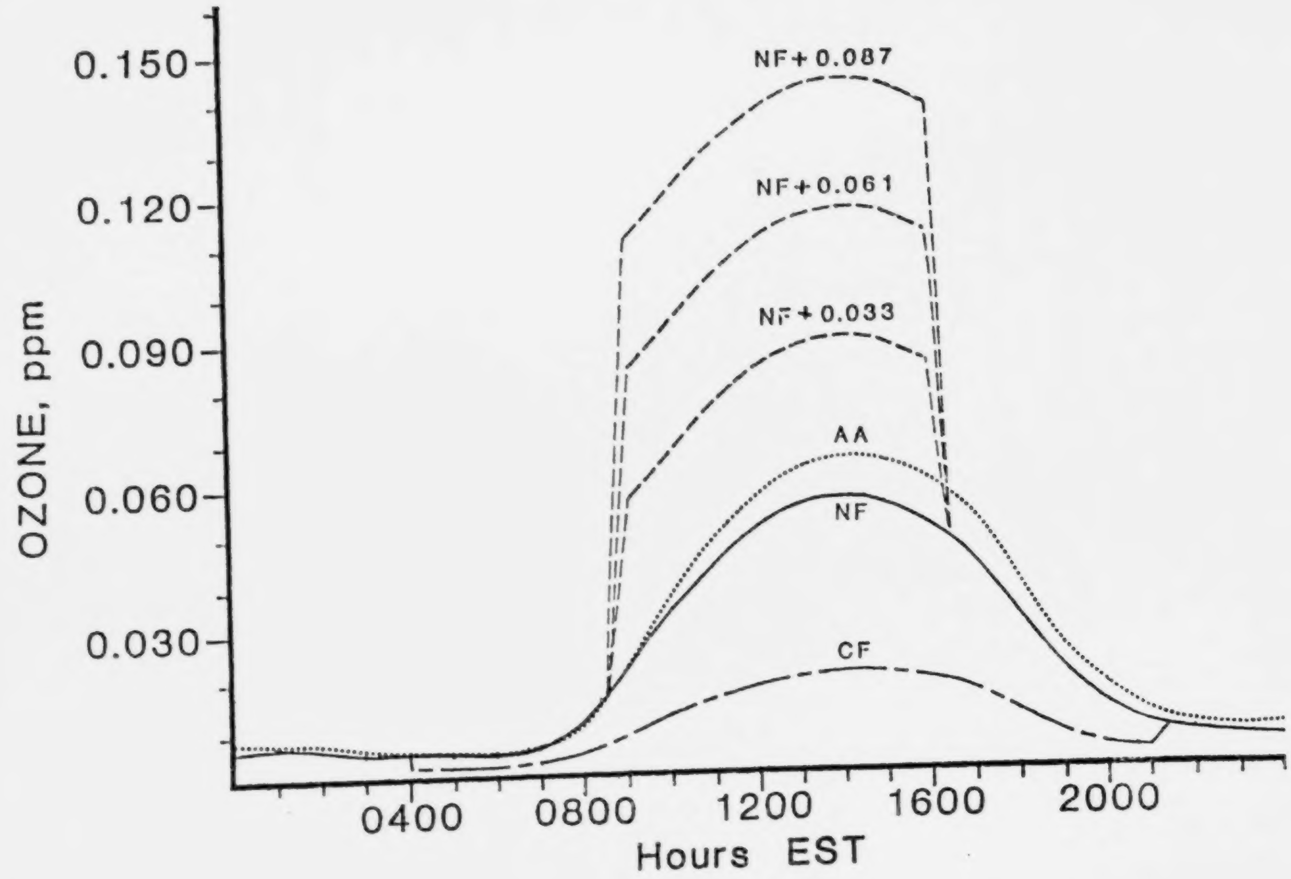

Figure 4.4.1.3. Seasonal mean fluctuations in O_3 levels from 8 July to 1 October for various treatments in the soybean study at Beltsville, Maryland.

TABLE 4.4.1.2. CHARACTERIZATION OF O_3 CONCENTRATIONS IN 5 TREATMENTS AVERAGED ACROSS 3 REPLICATIONS AND 2 LEVELS OF SOIL MOISTURE IN THE SOYBEAN STUDY AT BELTSVILLE, MARYLAND.

O_3 Treatment	7-h Means		7-h Exposure Period Means		Daily h Max		Daily h Max
	Fumigation Days, 81	Seasonal 86 Days	Highest	2nd Highest	Highest	2nd Highest	Average for Season
	ppm	ppm	ppm	ppm	ppm	ppm	ppm
CF	0.017	0.016	0.031	0.028	0.043	0.035	0.025
NF	0.049	0.047	0.084	0.081	0.110	0.102	0.063
NF + 0.03	0.078	0.075	0.120	0.113	0.145	0.137	0.089
NF + 0.06	0.106	0.100	0.148	0.143	0.179	0.170	0.116
NF + 0.09	0.132	0.125	0.176	0.171	0.205	0.195	0.142

* Data on a single plot basis showing 7-h seasonal means are in Table 4.4.1.3. Other O_3 characterizations for single plots are on file.

TABLE 4.4.1.3. MEAN O_3 AND SO_2 CONCENTRATIONS IN EACH CHAMBER FROM 8 JULY TO 1 OCTOBER.

	Moist Soil Series (-0.05 MPa)						
Pollutant	Plot #	ppm	Plot #	ppm	Plot #	ppm	$\bar{x}$
O_3	3	0.016	14	0.017	18	0.017	0.017
SO_2	3	0.002	14	0.026	18	0.092	0.040
O_3	1	0.044	9	0.046	16	0.049	0.046
SO_2	1	0.005	9	0.029	16	0.096	0.043
O_3	28	0.072	30	0.074	6	0.079	0.075
SO_2	28	0.005	30	0.027	6	0.094	0.042
O_3	8	0.096	12	0.103	25	0.102	0.100
SO_2	8	0.005	12	0.029	25	0.099	0.044
O_3	22	0.124	13	0.124	29	0.129	0.125
SO_2	22	0.005	13	0.029	29	0.092	0.042
$\bar{x}$ O_3		0.070		0.073		0.075	
$\bar{x}$ SO_2		0.004		0.028		0.095	

	Dry Soil Series (-0.44 MPa)						
Pollutant	Plot #	ppm	Plot #	ppm	Plot #	ppm	$\bar{x}$
O_3	10	0.014	19	0.027	27	0.020	0.017
SO_2	10	0.002	19	0.026	27	0.095	0.041
O_3	4	0.046	2	0.046	15	0.051	0.047
SO_2	4	0.005	2	0.028	15	0.095	0.042
O_3	24	0.071	5	0.076	11	0.075	0.074
SO_2	24	0.005	5	0.028	11	0.093	0.042
O_3	26	0.100	21	0.098	20	0.104	0.101
SO_2	26	0.005	21	0.028	20	0.094	0.042
O_3	23	0.124	7	0.125	17	0.126	0.125
SO_2	23	0.005	7	0.029	17	0.095	0.043
$\bar{x}$ O_3		0.071		0.072		0.075	
$\bar{x}$ SO_2		0.004		0.028		0.094	

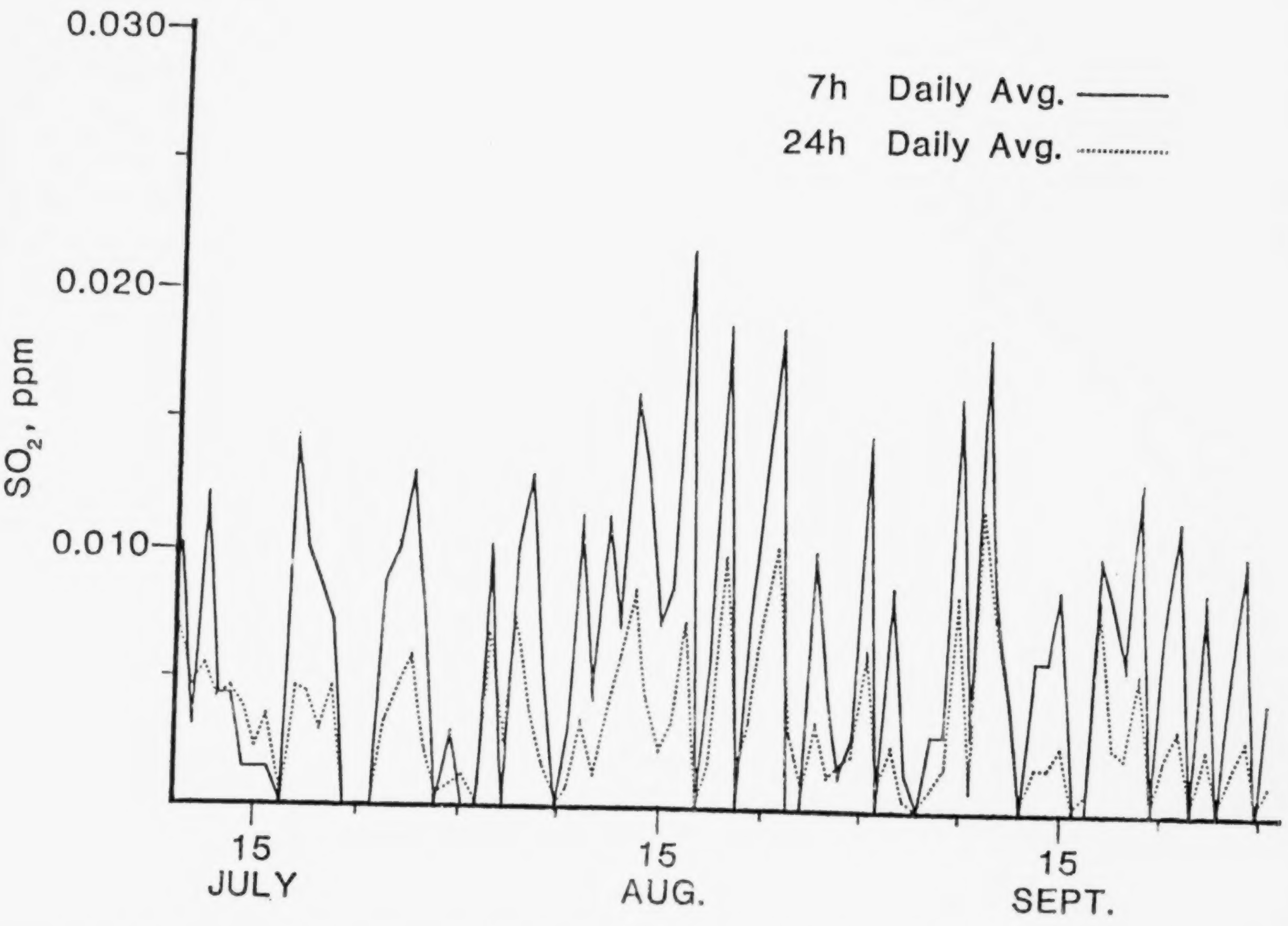

Figure 4.4.1.4. Ambient 7- and 24-h daily mean SO_2 concentrations from 8 July to 1 October at Beltsville, Maryland.

There was no improvement in experimental efficiency using the companion plots as a covariant; consequently, the unadjusted seed weights were used to evaluate the treatments. An ANOVA test was made on yield, seed size, and seed number. Linear regression and Weibull equations were developed for the response of each cultivar to O_3 and SO_2 at each of the two soil moisture levels.

4.4.1.3 Results

Seasonal Climate. Rainfall was below normal in July, August, and September (Table 4.4.1.1). This was an advantage as the rain exclusion devices were not needed until 24 August. Except for the high O_3 treated plots, which reduced water demand due to O_3 injury of the leaves, we were able to achieve the desired soil moisture tension, of about -0.44 MPa. Little rain occurred until 20 September, but by that time the cultivar Williams was nearing harvest maturity and Forrest was approaching physiologic maturity. Consequently, our inability to maintain as much soil moisture stress in the "dry" plots after 20 September had no effects on yields of Williams and little, if any, effect on yields of Forrest. Temperatures and sunlight were above normal during most of July, which may have been a factor in producing the season's highest levels of ambient O_3 in that month. In general, O_3 levels in 1982 were higher than in 1981 (see Heck et al., 1982b).

Leaf Injury and Senescence. Chlorosis on the upper surface of recently fully expanded leaves was observed 15 July, one week after the pollutant exposures began. The injury increased as concentrations increased. The average injury indices (0-10) for Williams and Forrest per chamber in the moist soil were 2.0, 3.8, and 5.2 for NF + 0.03, NF + 0.06, and NF + 0.09, respectively, and 0.05, 2.8, and 3.7, respectively, in the dry soil. Williams was injured more than Forrest. No visible injuries were observed on 15 July in CF and NF plots. By 20 July, plants of Forrest in the moist series with the highest O_3 and SO_2 exposure concentrations were very chlorotic. Although the addition of 0.10 ppm SO_2 increased leaf injury, SO_2 at 0.03 ppm/4-h day did not.

Leaf injury was again evaluated on 3rd and 25th of August (Table 4.4.1.4). The ANOVA test revealed that the main effects (O_3, SO_2, soil moisture, and cultivar) were significant. There were no significant interactions involving the main effects except O_3 x cultivar. The amount of injury on the two cultivars as related to the O_3 dose is shown in Table 4.4.1.5. Mean square values indicate that the effects of O_3 on leaf injury was 15 times greater than the effects of either SO_2 or soil moisture stresss.

The rate of leaf senescence was determined at about 2-week intervals by measuring the height to the first node with a fully green leaf (Table 4.4.1.6). As with leaf injury, the ANOVA test revealed significant effects of moisture, O_3, and SO_2 on senescence but no interactions among parameters. There was a significant interaction between the cultivars and soil moisture since Forrest had more tolerance to soil moisture stress than Williams (Table 4.4.1.9). Leaf senescence was similar in both cultivars in July and August. However, by early September when Williams was approaching physiological maturity it showed more senescence than Forrest, especially on the relatively dry soil. On 2 September, Forrest showed more senescence in the moist soil than in dry soil.

TABLE 4.4.1.4. EFFECTS OF SOIL MOISTURE STRESS ON POLLUTANT-INDUCED LEAF INJURY IN SOYBEANS.

Soil Moisture	Seasonal Mean 7-h O_3 Conc.* (ppm)	Leaf Injury Index (0, no injury -- 10)	
		3 August	25 August
Moist soil (-0.05 MPa)	0.016	0.42	1.33
	0.047	1.25	2.25
	0.075	3.67	4.00
	0.100	4.67	5.33
	0.125	5.17	6.50
Dry soil (-0.44 MPa)	0.016	0.0	0.83
	0.047	0.53	0.83
	0.075	2.50	2.58
	0.100	3.25	5.33
	0.125	5.25	6.50

* O_3 response is averaged across three SO_2 treatments, no added SO_2, and either 0.029 ppm or 0.010 ppm SO_2 added 4-h/day on 81 of 86-day period.

TABLE 4.4.1.5. LEAF INJURY ON TWO SOYBEAN CULTIVARS IN RESPONSE TO O_3 AT BELTSVILLE, MARYLAND.

Cultivars	Seasonal Mean 7-h O_3 Conc. (ppm)	(0, no injury -- 10)	
		3 August	25 August
Williams	0.016	0.17	0.92
	0.047	0.58	1.33
	0.075	2.33	3.00
	0.100	2.92	5.17
	0.125	4.08	6.17
Forrest	0.016	0.25	1.25
	0.047	1.20	1.75
	0.075	3.83	3.58
	0.100	5.00	5.50
	0.125	6.33	6.83

* O_3 response is averaged across three SO_2 treatments, no added SO_2, and either 0.029 ppm or 0.010 ppm SO_2 added 4-h/day on 81 of 86-day period.

TABLE 4.4.1.6. DIFFERENCES IN LEAF SENESCENCE SHOWN BY 2 SOYBEAN CULTIVARS ON 4 DATES AFTER EXPOSURE TO O_3 AND SO_2 ON PLOTS WITH AND WITHOUT SOIL MOISTURE STRESS AT BELTSVILLE, MARYLAND.

		to Node with First Green Leaf	
Cultivar	Date	Soil Moist	Soil Dry
		cm	cm
Williams	21 July	22.4	19.1
	04 August	48.5	40.4
	18 August	65.4	65.9
	02 September	119.5	108.3
Forrest	21 July	26.5	23.5
	04 August	40.5	43.8
	18 August	87.0	72.7
	02 September	126.7	86.7

TABLE 4.4.1.7. SUMMARY OF ANOVA TEST TO DETERMINE THE SIGNIFICANCE OF TREATMENT EFFECTS ON SOYBEAN YIELDS FROM SEASONAL EXPOSURES TO O_3, SO_2, AND SOIL MOISTURE STRESS AT BELTSVILLE, MARYLAND.

Source	df	Mean Square	F Value	P > F
O_3	4	53,613	20.1	0.0003**
SO_2	2	14,821	5.6	0.0308*
Soil Moisture	1	19,813	7.4	0.0261*
O_3 x SO_2	8	251	0.1	0.9985
O_3 x Moisture	4	9,271	3.5	0.0632
SO_2 x Moisture	2	103	0.0	0.9623
(O_3 x SO_2 x Moisture) Error a	8	2,672		
Cultivar	1	496	0.4	0.5602
O_3 x Cultivar	4	1,160	0.8	0.5266
SO_2 x Cultivar	2	2,605	1.0	0.1880
Moisture x Cultivar	1	9,533	6.8	0.0190*
O_3 x Moisture x Cultivar	4	2,540	1.8	0.1757
SO_2 x Moisture x Cultivar	2	3,719	2.7	0.1011
Error b†	16	1,401		
Total	59			

* Significance at $P = 0.05$ level.

** Significance at $P = 0.01$ level.

† Error B = the pooled "cultivar x O_3 x SO_2" and "cultivar x moisture x O_3 x SO_2."

TABLE 4.4.1.8. EFFECTS OF O_3 ON SOYBEAN YIELDS USING COMBINED DATA ON MOISTURE STRESS AND CULTIVARS AT BELTSVILLE, MARYLAND.

7-h O_3 8 July - 1 October	N	Soybean Yield (kg/ha)*	Percent of Yield in CF Air
CF 0.017	12	4689	100
0.047	12	4060	86.6
0.075	12	3542	75.5
0.101	12	3234	69.0
0.125	12	2810	59.9

* Means are for 6 plots: 2 varieties each plot, 2 SO_2 treatments, and 2 soil moisture levels.

TABLE 4.4.1.9. EFFECTS OF 2 SOIL MOISTURE REGIMES ON THE YIELDS OF TWO SOYBEAN CULTIVARS AT BELTSVILLE, MARYLAND.

Treatment	Yield of Cultivars Williams kg/ha	Yield of Cultivars Forrest kg/ha	Percent/Forrest Williams x 100
Soil Moist (-0.05 MPa)*	3972	3760	94.7
Soil Dry (-0.44 MPa)*	3299	3638	110.3
Percent, Dry/Moist x 100	83.1	96.8	

* Each value is the mean for 15 plots.

Yield Reductions. The yield data were subjected to an ANOVA test (Table 4.4.1.7). The effects of the main treatments (O_3, SO_2, and soil moisture) were significant, as was the cultivar by moisture interaction ($P > 0.02$). It should be noted that there was no evidence of an interaction between O_3 and SO_2 ($P > 0.9985$). This suggests that averaging O_3 effects across SO_2, and SO_2 effects across O_3 was justified.

Considering the combined cultivar data and the two soil moisture regimes, yields were significantly lower (-13.4%) in NF air than in CF air (Table 4.4.1.8). Each step increase in O_3 concentration significantly reduced yields. With the 7-h mean of 0.125 ppm O_3, yields were reduced 40% below those in CF air. The effects of soil moisture on the yields of the two cultivars are summarized in Table 4.4.1.9. Yields of Williams but not those of Forrest were reduced by soil moisture stress.

The yield of each cultivar was reduced about 29% when exposed to NF air (no O_3 added) under dry soil conditions (Table 4.4.1.10 and Figure 4.4.1.5). The addition of 0.03 ppm and 0.06 ppm O_3 under dry conditions caused none, or slight, yield reductions compared to NF air. Reducing the O_3 in ambient air (as in CF air) enabled the cultivars to withstand significant moisture stress without yield reductions. Combined yields of the two cultivars were essentially the same in CF air at the two moisture levels and in NF air when there was no moisture stress.

Forrest yielded 19% more in the CF dry soil than in the CF-moist soil (Table 4.4.1.10). About 24 September, Forrest appeared to have cold injury; i.e., severe chlorosis on leaves near the top of the plant canopy. The injury did not occur in the CF dry soil plots and it was only moderate in the NF moist soil plots. The injury may have reduced yields in the CF-moist soil since it developed about one month before harvest. Williams was fully mature in both moist and dry soil plots when the cold injury was observed in Forrest.

O_3 in ambient air reduced the seed size of Williams significant (6%) and each step increase in O_3 dose caused further reduction in seed size (Table 4.4.1.11). The cultivar by O_3 interaction was highly significant. Only at the two highest levels of O_3 exposure was seed size of Forrest significantly less than for the CF air treatment.

There was a significant reduction in the yield (14%) of soybeans exposed to 0.10 ppm SO_2 for 4-h/day (0900-1300) on 81 days of the 86-day season, 8 July - 1 October (Table 4.4.1.12). Exposure to 0.029 ppm SO_2 for the same time period had no measurable effect on yield.

Linear regression equations are provided in Table 4.4.1.13 for the yield of the two cultivars grown under the two soil moisture conditions and exposed to O_3 and SO_2. All regression lines show significant treatment effects on yield except for the SO_2 equation for Forrest grown with no soil moisture stress. The r^2 values for Williams were higher than for Forrest. The r^2 values were computed within cultivar and moisture and after adjusting the total variation for the effects of SO_2 when computing the O_3 equation and for O_3 when computing the SO_2 equation. For example, see $r^2 = 0.394$ for the equation showing effects of O_3 on Forrest in the moist soil series.

TABLE 4.4.1.10. RESPONSE OF SOYBEAN CULTIVARS TO O_3 WITH PLANTS GROWN WITH AND WITHOUT SOIL MOISTURE STRESS AT BELTSVILLE, MARYLAND.*

					Soil Moisture Potential					
	7-h Average 7/8 - 10/1				Moist (-0.05 MPa)			Dry (-0.44 MPa)		
			Number Plots		Seed Yield (kg/ha)			Seed Yield (kg/ha)		
O_3** Treatment	After 81 Days of Fumigation	During Season, 86 Days	Moist	Dry	W†	F†	Ave.	W†	F†	Ave.
CF	0.017	0.016	3	3	5130	4100	4615	4482	5046	4764
NF	0.049	0.047	3	3	4790	4730	4760	3193	3528	3361
NF + 0.03	0.078	0.075	3	3	3964	3614	3789	3195	3396	3296
NF + 0.06	0.106	0.100	3	3	3064	3441	3253	3093	3337	3215
NF + 0.09	0.132	0.125	3	3	2914	2912	2913	2534	2881	2708
					Percent of Yields in CF Air					
					100	100	100	100.0	100.0	100.0
					93.4	115.4	103.1	71.2	70.0	70.5
					77.3	88.1	82.1	71.3	67.3	69.2
					59.7	83.9	70.5	69.0	66.±	67.5
					56.8	71.0	63.1	56.5	57.1	56.8

* O_3 averaged across plots with no SO_2 added and with 4-h exposure to either 0.029 or 0.100 ppm SO_2.

** CF = charcoal filtered; NF = nonfiltered ambient air.

† W = Williams, F = Forrest.

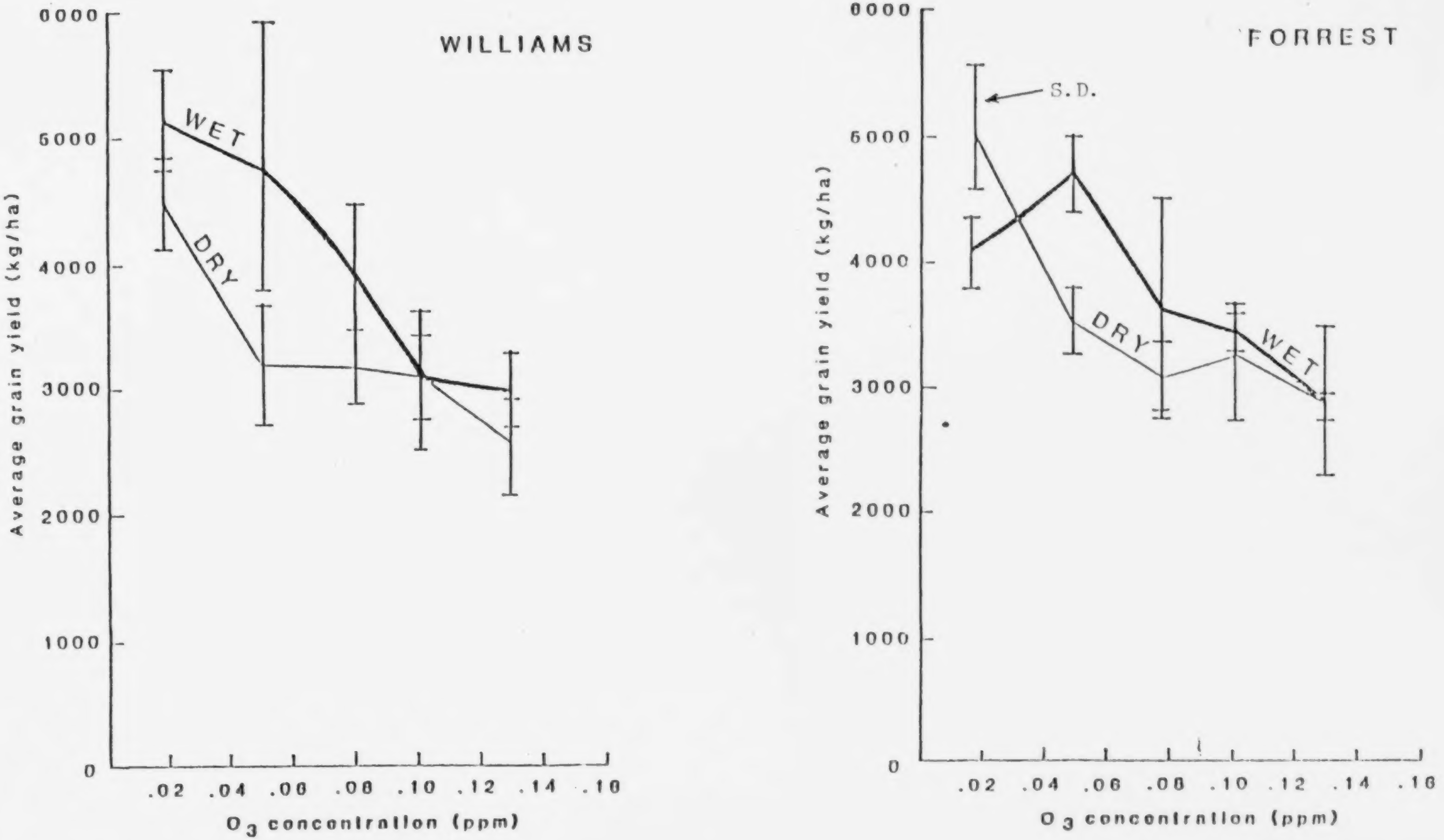

Figure 4.4.1.5. Effects of O_3 on soybean yields in wet and dry soils, means of two cultivars. Yield of 3 ambient air plots (no chambers) which received no irrigation was 259 g/m/row compared to 307 g/m/row for the NF chamber plots.

TABLE 4.4.1.11. EFFECTS OF O_3 ON SEED SIZE OF WILLIAMS AND FORREST AT BELTSVILLE, MARYLAND.

O_3 7-h* Means (ppm)	Seed Size (g/100 seeds)			
	Williams	% of CF**	Forrest	% of CF**
0.017 (CF)	19.1	100	13.1	100
0.049	17.0	93.7	13.4	102.3
0.078	16.5	86.4	12.7	96.9
0.106	15.4	80.6	11.9	90.8
0.132	1.44	75.4	11.5	87.8

* Data average of 6 plots: 3 SO_2 levels and 2 levels soil moisture stress.

** CF = charcoal-filtered air.

TABLE 4.4.1.12. RESPONSE OF SOYBEAN CULTIVARS TO SO_2 IN OPEN-TOP CHAMBERS WITH TWO LEVELS OF SOIL MOISTURE AT BELTSVILLE, MARYLAND.

Treatment 4-h SO_2 (ppm) 8 July - 1 October		Soil Moisture Potential					
		Moist (-0.05 MPa)			Dry (-0.44 MPa)		
After 81 Days Fumigation	During Season 86 Days	Seed Yield (kg/ha)*			Seed Yield (kg/ha)*		
		W**	F**	Ave.	W**	F**	Ave.
0.005	0.005	4466	3677	4072	3425	3873	4649
0.029	0.028	4010	3965	3988	3592	3703	3648
0.100	0.094	3441	3637	3539	20.01	3338	3110
		Percent of Yield with No SO_2 Added, i.e., 0.005 ppm SO_2					
		100	100	100	100	100	100
		89.8	107.8	97.9	104.9	95.6	100
		77.0	98.9	86.9	84.1	86.2	85.2

* Averages are across 5 levels of O_3 (see Table 4.4.1.10).

† W = Williams, F = Forrest.

TABLE 4.4.1.13. REGRESSION EQUATIONS FOR SEED YIELD DATA USING O_3 AND SO_2 CONCENTRATIONS FOR EACH PLOT AT BELTSVILLE, MARYLAND.

Cultivar	Soil Moisture	Equation (kg/ha)	r^2
Forrest	Moist	Yield = 4583 - 11122 (O_3)	0.394
	Dry	Yield = 4882 - 16317 (O_3)	0.689
Williams	Moist	Yield = 5570 - 21566 (O_3)	0.776
	Dry	Yield = 4406 - 14512 (O_3)	0.704
Forrest	Moist	Yield = 3817 - 1290 (SO_2)*	0.013
	Dry	Yield = 3890 - 5720 (SO_2)	0.450
Williams	Moist	Yield = 4441 - 10586 (SO_2)	0.619
	Dry	Yield = 3601 - 6857 (SO_2)	0.504

* This regression line only is not significantly different at P = 0.05 level).

Source	SS
Total	72,951
O_3	27,417
SO_2	3,422

$$r^2 = \frac{27,417}{72,951 - 3,422} = 0.394$$

Weibull equations relating yield (kg/ha) to seasonal 7 h/day mean O_3 concentrations are presented in Table 4.4.1.14. These equations were developed by Dr. W. W. Cure, Department of Botany, North Carolina State University, Raleigh.

Stomatal conductance data for Forrest and Williams were obtained just after midday on sunny and cloudy days to assess the effect of soil moisture stress and the pollutants on stomatal diffusion (Table 4.4.1.15). Midday stomatal conductances for plants growing on sunny days in dry plots were approximately half those observed for the wet plots. On cloudy days, the stomatal conductance of plants in the dry and wet plots were not as different, especially for the cultivar Williams. The dry plot mean conductances measured on cloudy days were similar to those found in the wet plots on sunny days. The Forrest cultivar exhibited lower mean conductances than Williams. For the leaves sampled, pollutant uptake rates by the leaf mesophyll tissues would be expected to be proportional to the ratios given in Table 4.4.1.15 for the various conditions indicated. Since our pollutant exposures were conducted on all days except when rainfall occurred, the impact of the pollutant exposures would be some function representative of exposures on both sunny and cloudy days.

4.4.1.4 Discussion

The water potentials observed in the moist plots were consistent and of the desired magnitude, -0.05 MPa. On the plots exposed to a moderate stress (-0.44 MPa), the soil water potentials were not as consistent but were low enough to estimate the impact of the phytotoxicants on the water uptake distribution. The data suggest that much of the variability was due to the pollutant treatments. As the O_3 concentration increased, the bottom psychrometers became nonfunctional. For example, in the NF + 0.09 ppm treatment, both of the psychrometers at 45 and 65 cm were nonfunctional. Likewise, for the NF + 0.06 ppm treatment, only the psychrometer at 65 cm was nonfunctioning. This trend was continued in the controls where psychrometers at all three depths were functional. These observations were due to the fact that soil psychrometers cannot monitor potentials greater than -0.15 MPa. Based on the psychrometer data the plants extracted less water from the lower depths as the O_3 exposures were increased. Also the soybean plants exposed to the NF + 0.09 ppm O_3 treatment may have extracted most of its water above 25 cm.

The analysis of variance infers that the O_3 and SO_2 treatments can be combined since $P > 0.998$. Consequently, for each cultivar, each O_3 treatment would have three replicates, while SO_2 would have five. Additionally, this indicates that O_3 and SO_2 had an additive effect on yield reduction for these

TABLE 4.4.1.14. WEIBULL EQUATIONS* RELATING YIELD (kg/ha) TO SEASONAL 7 h/day MEAN O_3 CONCENTRATION (ppm) AND SEASONAL 4 h/day MEAN SO_2 CONCENTRATION.†

Variety	Soil Moisture	Model
Forrest	Moist	$y = [4333 + (464.2 \times SO_2)] \exp [-(x/0.171)^{2.752}]$
	Dry**	$y = [5384 - (6565 \times SO_2)] \exp [-(x/0.205)^{1.000}]$
Williams	Moist	$y = [5884 - (12610 \times SO_2)] \exp [-(x/0.162)^{1.577}]$
	Dry**	$y = [4880 - (7697 \times SO_2)] \exp [-(x/0.217)^{1.000}]$

* Estimates of model parameters were adjusted by an extension of the α parameter to accommodate the effects of SO_2:

$$y = [\alpha + \beta\ (SO_2 \text{ Concentration})] \exp [-(x/\hat{\sigma})^{c}]$$

** To insure proper convergence, it was necessary to place a lower bound of 1.000 on the c parameter during the nonlinear model fitting routine (PROC NLIN of SAS).

† Table courtesy Dr. W. W. Cure, Department of Botany, North Carolina State University.

TABLE 4.4.1.15. MEAN STOMATAL CONDUCTANCE FOR SOYBEAN LEAVES TAKEN MIDDAY ON ONE SUNNY AND ONE CLOUDY DAY AT BELTSVILLE, MARYLAND.

	Mean Stomatal Conductance (cm sec^{-1})*					
	Sunny		Ratio	Cloudy		Ratio
Variety	Dry Soil	Wet Soil	Dry/Wet	Dry Soil	Wet Soil	Dry/Wet
Forrest	0.57	1.20	0.5	1.10	1.90	0.6
Williams	0.80	1.34	0.6	1.57	2.05	0.8
Ratio: Forrest/Williams	0.7	0.9		0.6	0.9	

* Each value based on 30 experiments; i.e., 2 dates, 3 leaves on each cultivar in 5 chambers each exposed to a different level of O_3.

cultivars. The cultivar results were surprisingly similar. For example, both cultivars exhibited a 30 percent reduction in yields when exposed to the nonfiltered air under dry conditions. No significant reduction in yields was evident for either cultivar in the nonfiltered wet plots without added O_3, suggesting that the moist conditions enabled the cultivars to tolerate ambient O_3 concentrations. The reduction in yields by the Forrest cultivar when exposed to CF air and a high soil water potential is believed due to cold injury in mid-September, about 6 weeks before harvest maturity. The cold injury did not develop in plots with low soil water potential. The CF plots with high soil water potential had abundant green foliage just prior to the development of cold injury.

Very different conclusions would be made if the CF "clean air" control were not a part of the experiment. Without the CF control one would conclude that the dry soil conditions (water potential, -0.44 MPa) prevented yield losses following exposure to all except the highest O_3 concentration (NF + 0.09 ppm). Also, the 30% yield decrease in NF air was due to inadequate soil moisture. However, there was no yield decrease due to moisture stress in the CF control and the soil moisture potentials at the depths monitored were about the same as in chambers with CF and NF air.

When the data are combined for cultivars and the two soil moisture regimes, yield reductions (-13%) were significant in NF air compared to CF air. Regression and Weibull equations were developed to show yield losses by each cultivar when O_3 concentrations were increased and plants were grown with and without soil moisture stress.

In the absence of stresses from pollutants and soil moisture, Williams yielded more than Forrest, even though Forrest took nearly 4 weeks longer than Williams to mature.

4.4.1.5 Conclusion

This study demonstrates that there was a very large (30%) decrease in soybean yields when both soil moisture stress and ambient concentrations of O_3 were present. However, eliminating moisture stress seemed to enable the plants to tolerate the average ambient concentration of O_3 experienced in this investigation (0.047 ppm, 7-h mean). Under moist conditions, there is a linear decrease in yields with increasing concentrations of O_3; however, under dry conditions, an increase in O_3 levels over that in ambient air shows only a slight decrease in yields. The liberal use of supplemental irrigation did not cause the effects of O_3 in ambient over to be overestimated.

4.4.2 Effect of O_3 on Growth of Well Watered and Water Stressed Soybean (NERCLAP)*

4.4.2.1 Introduction

Water stress has been shown to reduce foliar injury induced by O_3 presumably by reducing pollutant uptake through stomatal closure (Olszyk and Tibbitts, 1981). However, few studies have quantified changes in leaf conductance with defined moisture stress (Tingey et al., 1982), or assessed the interaction of moisture stress and O_3 on crop growth and yield. In this study, the effect of O_3 on growth, biomass accumulation, flowering, and fruit set of well watered and water stressed plants was assessed for plants grown in controlled environment chambers.

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* Robert Amundson, Boyce Thompson Institute.

One of the strengths of data collected in the NCLAN program is that the crops are cultured in the field under conditions as close to common agricultural practices as possible. Therefore changes in yield can be directly attributed to the respective O_3 exposures and regression equations can be generated that describe the relationship between dose of O_3 and yield for that crop. Ideally the effects of water stress on O_3 dose-response functions for crop yields should be generated under field conditions. However, several factors that need to be controlled or at least monitored can make these experiments expensive and sometimes unrepeatable. For example, ambient rain may or may not have to be excluded from specific treatments and within a field there can be wide differences in drainage and soil moisture holding capacity.

This experiment was conducted under controlled environmental conditions to eliminate factors that potentially could interact individually or jointly with the O_3 stress and/or the water stress. Furthermore, changes in net photosynthesis, net assimilation rates, and stomatal conductance were more effectively monitored in the laboratory and these measurements helped to explain the cause and effect relationships of the two stresses.

4.4.2.2 Materials and Methods

Plant culture. Seeds (Glycine max cv. Hodgson) were planted in a 1:1:1 (v:v) mixture of peat, perlite, and soil in 3.5 liter pots on 2 February 1982 and placed in a temperature controlled greenhouse in Ithaca, New York. Seedlings emerged on 17 February and 9 days later vigorous plants were randomly assigned to four controlled environment growth chambers (Western Environmental, Napa, California). Chamber conditions included 16-h photoperiods with half-lights for the first and last half hours of each photoperiod. Day/night temperatures were 26/21 ± 1°C and PAR at the top of the plant canopy was approximately 700 μmole m^{-2} s^{-1}. Plants were fertilized twice weekly with a modified (3x) North Carolina State University Phytotron nutrient solution (Downs and Hellmers, 1975).

Experimental design. The experiment was designed with two moisture treatments (high and low watering regimes) within each of four O_3 treatments (0.01, 0.05, 0.09, or 0.13 ppm). Plants from each treatment (eight in all) were destructively harvested at four two-week intervals. The experiment was an unblocked 2 x 4 x 4 with six plants per treatment for each harvest. Data were analyzed by analysis of variance and regression equations for the effects of O_3 on biomass of roots, stems, and leaves were calculated by regression analysis.

O_3 treatments. Plants were exposed daily (growth stages V2-R4; Fehr and Caviness, 1977) to O_3 concentrations of either 0.01, 0.05, 0.09, or 0.13 ppm for approximately 6.8 hours per day. Daily mean concentrations during exposures were within 0.01 ppm of the respective treatment mean concentrations. Treatments were rotated weekly from chamber to chamber so that after 8 weeks all treatments had been housed in each growth chamber for 2 weeks. Also, within each treatment, the position of plants within a chamber was randomly varied during the weekly chamber rotation. During the end of the third week of exposure, the chamber in which the 0.01 ppm O_3 was being dispensed malfunctioned and all plants in that treatment were subjected to high temperatures. Thus, these plants were not used in analyses for harvests 3 and 4.

Moisture treatments. One week after exposures began, water was withheld from half of the plants in each O_3 treatment for 3 or 4 consecutive days per week (water stressed). The fertilization regime remained the same for both moisture treatments. To indicate severity of the water stress through the course of the drying cycle, a steady-state porometer (Model 1600, LiCor, Lincoln, Nebraska) was used to monitor stomatal conductances, while a Scholander pressure chamber (PMS, Corvallis, Oregon) was used to measure xylem pressure potentials (XPP) at harvest which corresponded to the last day of that water stress cycle. Since the plants that were not harvested were watered an hour or two before the XPP were determined, the XPP measurements indicated the minimum XPP of plants in each treatment for that water stress cycle.

Measurement of plant growth. Six plants from each of the eight treatments were harvested 13, 27, and 40 days after the exposures began. Between harvests 2 and 3, an infestation of two-spotted spider mites (Tetranychus urticae) was noted on the water stressed plants in all chambers. The infestation was partially controlled by application of Kelthane to individual leaves by sponge. To reduce the spread of spider mites to the well watered plants, the water stressed plants were harvested one week earlier than the well watered plants at harvest 4 (47 and 55 days after the exposures began, respectively). There appeared to be no correlation with spider mite infestation and O_3 treatment. For each harvest, plant height, node number above the cotyledons, leaf area (LICOR Model H-3100), leaf, stem, and root dry weights were recorded for each plant. In addition, pod dry weights and pod number were recorded at harvest 4. The age of each leaf on the primary stem was determined by noting its node number and the date on which the leaf blade was fully unrolled. The leaf was assigned the age of zero for that date. The leaf was later identified by the node number and its age was used for pairing with measurements of net photosynthesis, xylem pressure potentials, and stomatal conductances for all treatments. The date of leaf abscission was also recorded for each of the leaves on the primary stem. The date of flower opening and the node number of the initial flowering on the primary stem was also recorded for each plant.

CO_2 exchange. Net photosynthetic rates (P_n) were assessed both for individual leaves and for whole plants. Rates of net photosynthesis for individual leaves were assessed by enclosing intact leaves in either of two thermoelectrically cooled and heated cuvettes (Kananaskis Centre for Environmental Research, Alberta, Canada). An open gas exchange system was used and the CO_2 concentrations were monitored by an infrared CO_2 analyzer (Anarad, Model AR-600) that was calibrated daily in the differential mode using certified CO_2 standard gases (Scott Specialty Gases, Plumsteadville, Pennsylvania).

Rates of net photosynthesis for whole plants were monitored by using continuously stirred tank reactors (CSTRs) modified from the design of Rogers et al. (1979). Plants were transferred from the growth chambers to the CSTRs for a period of 1-3 d. Measurement of CO_2 mass balance and calibration of instruments were made as for individual leaves. The total leaf area of the plant was estimated by measuring the length of each leaflet and then calculating its area according to the following equations:

Terminal Leaflet: log area (cm^2) = -6.93 - 2.22 (log leaflet length); $r^2 = 0.97$.

Lateral Leaflets: log area (cm^2) = -6.63 - 2.26 (log leaflet length); $r^2 = 0.92$.

These equations were derived by regressing measured leaflet length to measured leaflet area for 84 terminal and 84 lateral leaflets, respectively. Also, in an attempt to assess whether the effects of O_3 treatments upon whole plant net photosynthesis were comparable with treatment effects upon dry matter accumulation, net assimilation rates (NAR) were calculated according to Woodruff (1969), as follows:

$$\frac{(DW_2 - DW_1)\ (\ln LA_2 - \ln LA_1)}{(t_2 - t_1)\ (LA_2 - LA_1)}$$

where DW_1 and DW_2 are plant dry mass at times 1 and 2, respectively, LA_1 and LA_2 are leaf area at times 1 (t_1) and 2 (t_2), respectively.

Chlorophyll contents. At three times during the experiment (after 27, 40, and 55 days of O_3 exposure), leaf disks were collected from various aged trifoliolates in each well watered treatment. At each harvest, a 0.61 cm^2 disk was taken from each side of the midvein of the central leaflet in 4 trifoliolates (from different plants) of four to six ages within each treatment. The two disks per leaflet were combined into a composite sample and each leaf was considered a replicate sample. Leaf disks were homogenized in 80% acetone and leaf Chl a + b contents were determined for each sample according to the methods of Arnon (1949). Also, mean leaf Chl a + b contents were estimated for each plant by averaging all sampled leaves.

4.4.2.3 Results

Effect of O_3 on harvest variables. The effect of O_3 on plant growth was altered by the different soil moisture treatments when tested by AOV, therefore the mean squares of the AOV for effect of O_3 on the harvest variables measured are presented separately for the well-watered and water-stressed plants (Table 4.4.2.1).

The average petiole xylem pressure potential (XPP) of young, fully expanded trifoliolates of both well watered and water stressed plants at harvests 1, 2, and 3 are shown in Figure 4.4.2.1. At harvest 1, there was a trend for lower XPP in the water stressed plants. As the plants grew, the average XPP at midday on the dates of harvest declined to about -0.6 MPa in the well watered plants, whereas the XPP of the water stresed plants declined

TABLE 4.4.2.1. MEAN SQUARE TABLE OF ANALYSIS OF VARIANCE OF HARVEST VARIABLES OF SOYBEANS MAINTAINED ON TWO WATERING REGIMES [WELL WATERED (W) AND WATER STRESSED (D)] AND EXPOSED TO FOUR CONCENTRATIONS OF O_3 FOR 13, 17, 40, OR 47 AND 55 DAYS (HARVESTS 1, 2, 3, AND 4,† RESPECTIVELY).

				Mean Squares					
						Dry Weight (g)			
Harvest		Source	df	Plant Height (cm)	Leaf Area (cm^2)	Leaf	Stem	Root	Total
1	W	OL	1	10,963**	1,364,907**	4,048**	1864*	2279*	23,885**
		OQ	1	2	66,360	392	35	210	1,617
		OC	1	1	12,080	14	0	8	1
	D	OL	1	1,960	1,776,820**	4,201**	1,763**	10,452**	43,701**
		OQ	1	84	84,996	204	3	1,121	434
		OC	1	630	316,830	1,080	333	241	4,441
2	W	OL	1	15,300*	20,183,914**	173,812**	148,544**	39,422*	1,001,744**
		OQ	1	39,609**	10,532,822*	3,337	18,150	24,768	1,233
		OC	1	35	277,248	848	930	75	2,595
	D	OL	1	6,092	649,001	12,100	6,825	17,910	106,564
		OQ	1	13,301*	105,966	5,922	9	4,267	216
		OC	1	8	203,555	11,117	5,267	12,444	83,847
3	W	OL	1	19,200*	73,508,053**	1,496,014**	1,591,408**	853,333**	11,617,104**
		OQ	1	20,544*	1,006,793	27,611	82,177	4,624	148,096
	D	OL	1	24,752*	4,400,287	165,400*	158,470	115,836**	1,311,424*
		OQ	1	200	1,663,688	19,928	19,274	25,760	194,040
4†	W	OL	1	1,492,675**	22,072 x 10^5**	7,019,640**	5,361,370**	240,390*	42,906,790**
		OQ	1	260,100*	3,705 x 10^5*	1,349,469**	193,767	395,431	1,119,011
	D	OL	1	13,333*	2,074 x 10^5	163,867	168,744	79,056	1,191,960
		OQ	1	5,136	1 x 10^5	22,500	5,304	16,813	44,100

* = $P < 0.05$.

** = $P < 0.01$.

† For harvest 4, the water stressed plants were harvested after 47 days of exposure to O_3 while the well watered plants were harvested after 55 days of exposure.

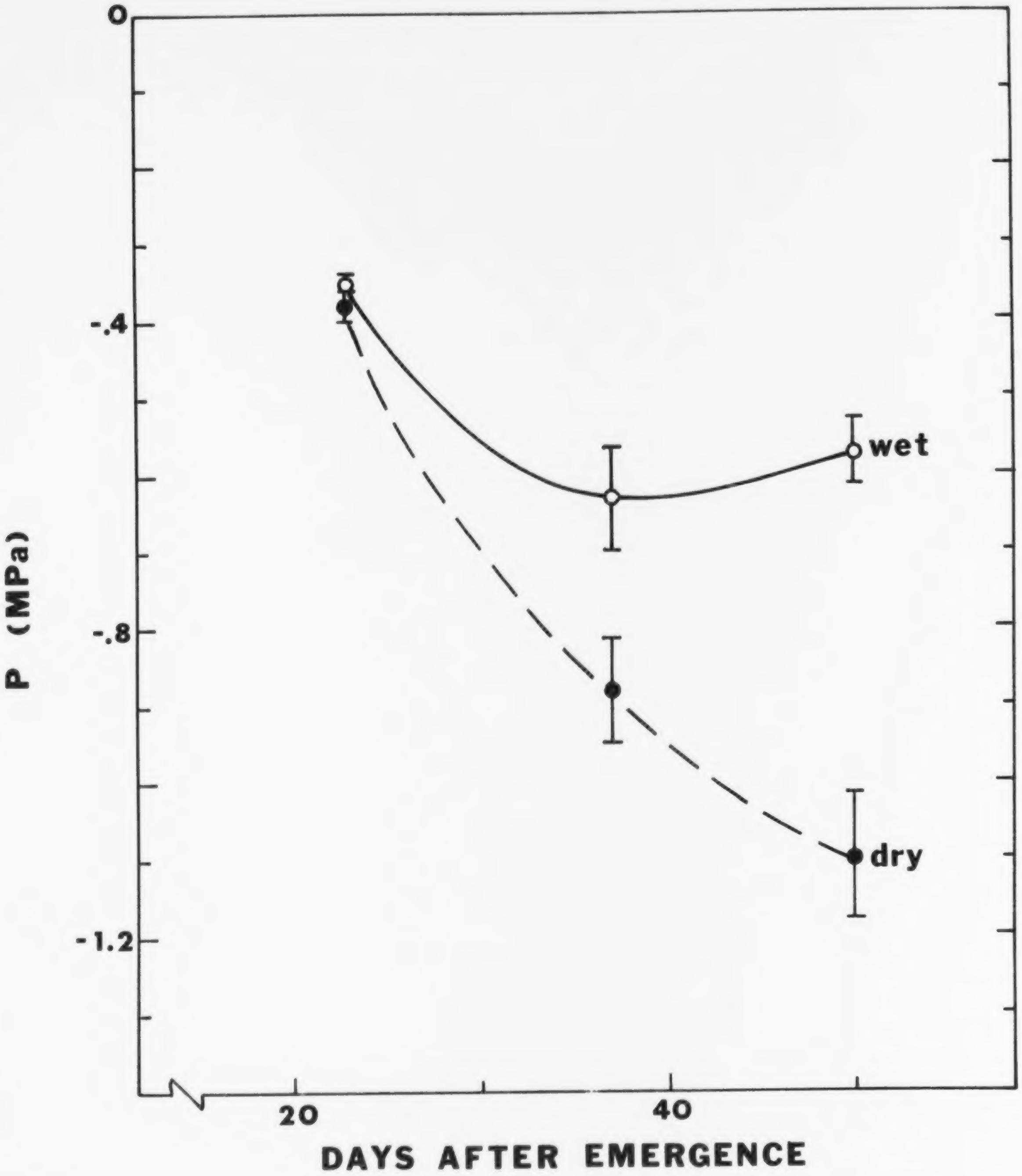

Figure 4.4.2.1. Xylem pressure potentials (XPP) of soybeans maintained on two watering regimes. Measurements were made at harvest and represent the minimum XPP for that period. Well watered plants (0, wet) and water stressed plants (●, dry).

to -0.9 MPa at harvest 2 and -1.1 MPa at harvest 3. The comparison was not made for harvest 4 because the water stressed plants were harvested one week earlier than the well watered plants.

Well watered plants -- In general, all harvest variables measured (height, leaf number, leaf area, leaf thickness, and dry weight of leaf, stem, and root) decreased linearly with increasing O_3 concentrations at all four harvests except for a quadratic reduction in leaf number with increasing O_3 concentration at harvests 2 and 4 (Table 4.4.2.1 leaf number and thickness not shown).

Water stressed plants -- At the first harvest, after two weeks of exposure to O_3 but after only one week of different watering regimes, the responses to O_3 were similar for the well watered and water stressed plants. Exposure to increasing concentrations of O_3 produced linear reductions for all harvest variables except for no effect of O_3 on plant height, leaf number, or leaf thickness for the water stressed plants (Table 4.4.2.1 leaf number and thickness not shown). At harvest 2, only quadratic decreases with increasing O_3 concentrations were found in plant height and leaf thickness in the water stressed plants; however, at harvest 3, there were linear decreases in plant height, leaf thickness, total weight, aboveground weight, leaf weight, and root weight. At the final harvest, the only effect was a linear reduction in plant height with increasing concentration of O_3.

Effect of O_3 on biomass accumulation and allocation. The differences in biomass accumulation (root, stem, and leaf dry weight) produced by the three higher O_3 treatments and the two moisture treatments are shown in Figure 4.2.2.2. The well watered plants were all larger than the water stressed plants after three weeks of treatment with different watering regimes regardless of O_3 concentration. In the well watered plants, an inverse relationship between O_3 concentration and plant growth was established after only two weeks of O_3 exposure and that inverse relationship was maintained through the final harvest. In the water stressed plants, an inverse relationship was found between O_3 treatments and aboveground biomass also after two weeks of exposure to O_3; however, that relationship was not significant for all four harvests.

The percentage of the total biomass allocated to roots, stems, or leaves changed as the plants grew, but the O_3 and watering treatments had little or no effect on biomass allocation (Table 4.4.2.2). In general, for all treatments at harvest 1, the biomass was distributed approximately as follows: 45% in roots, 25% in stems, and 30% in leaves; by harvest 4 the biomass distribution was about 25-30% in roots, 40% in stems, and 30% in leaves regardless of treatment.

The estimated linear regressions for the effect of O_3 on root, stem, leaf and total dry weights are given in Table 4.4.2.3. Heck et al. (1982) stated that 0.025 ppm O_3 could be used as an estimate of the natural O_3 background concentration in the absence of anthropogenic pollution. The predicted percentage reductions for leaf, stem, root, and total dry weights from the estimated biomass of plants exposed to 0.025 ppm O_3 (set at 100%) are given in Table 4.4.2.4. At each harvest, the estimated percent reductions of leaf, stem, root, or total dry weight were approximately the same for each O_3 concentration within each moisture stress treatment. However, the percent

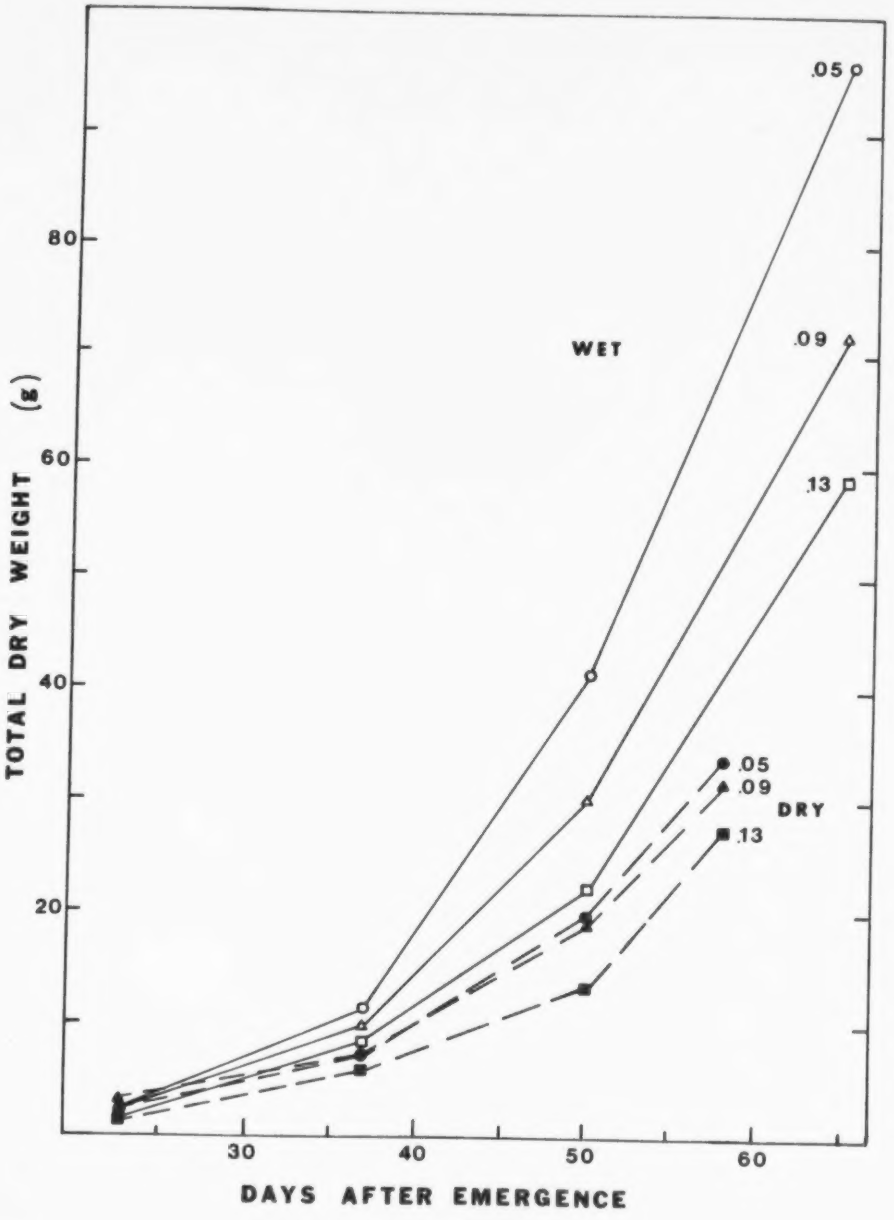

Figure 4.4.2.2. Effect of different watering regimes (——, wet; ---, dry) and O_3 concentrations (●, ○ = 0.05; ▲, △ = 0.09, ■, □ = 0.13 ppm) on biomass accumulation of soybean.

TABLE 4.4.2.2. EFFECT OF O_3 ON BIOMASS ALLOCATION TO ROOTS, STEMS, LEAVES, OR PODS OF SOYBEANS MAINTAINED ON TWO WATERING REGIMES.

		Biomass Allocation (% of Total Dry Weight)*							
		Well Watered				Water Stressed			
O_3 (ppm)	Harvest	0.01	0.05	0.09	0.13	0.01	0.05	0.09	0.13
Root (d.w.)	1	42†	42	44	47	50	44	47	48
	2	22	29	29	24	38	33	33	37
	3	26	29	26		29	29	28	
	4	25	31	26		28	29	28	
Stem (d.w.)	1	25	24	24	24	22	23	23	23
	2	38	33	33	38	31	32	31	33
	3		39	37	40		38	37	39
	4		40	42	44		39	37	39
Leaf (d.w.)	1	33	34	32	29	28	33	30	28
	2	40	38	38	39	31	35	36	30
	3		35	34	34		34	34	33
	4		34	26	29		33	34	32
Pod (d.w.)	4		0.3	0.2	0.5		0.1	0.1	0.1

* % of total dry weight.

TABLE 4.4.2.3. LINEAR REGRESSION EQUATIONS FOR EFFECT OF O_3 ON ROOT, STEM, LEAF, AND TOTAL DRY WEIGHTS (g) OF SOYBEAN MAINTAINED ON TWO WATERING REGIMES AND EXPOSED TO O_3 (0.01, 0.05, 0.09, or 0.13 ppm) FOR 2, 4, 6, OR 8 WEEKS (HARVESTS 1-4, RESPECTIVELY).

		Well Watered				Water Stressed			
Harvest	Dry Weight	m† Slope	b†† Intercept	R^2	F	m Slope	b Intercept	R^2	F
1	Leaf	-2.90	0.87	0.37	13.03**	-2.96	0.91	0.32	10.20**
	Stem	-1.97	0.64	0.32	10.59**	-1.92	0.66	0.30	9.46**
	Root	-2.18	1.04	0.20	5.54*	-4.67	1.43	0.36	12.14**
	Total	-7.05	2.55	0.32	10.57**	-9.54	3.01	0.39	14.15**
2	Leaf	-19.03	5.34	0.33	10.75**	-5.02	2.53	0.08	1.89
	Stem	-17.59	4.94	0.28	8.68**	-3.77	2.34	0.05	1.13
	Root	-9.06	3.29	0.18	4.87*	-6.11	2.73	0.09	2.30
	Total	-34.68	13.57	0.30	9.56**	-14.90	7.61	0.08	2.04
3	Leaf	-88.27	18.79	0.72	41.93**	-29.35	8.34	0.26	5.75*
	Stem	-91.04	20.21	0.70	38.10**	-18.73	8.98	0.19	3.82†
	Root	-66.67	14.43	0.48	14.19**	-24.56	7.01	0.35	8.43**
	Total	-245.98	53.43	0.68	33.25**	-82.65	24.33	0.28	6.16*
4	Leaf	-191.20	39.95	0.75	47.17**	-29.13	12.74	0.16	3.03
	Stem	-167.10	46.41	0.61	24.72**	-29.65	14.32	0.11	1.92
	Root	-111.18	30.55	0.21	4.27†	-20.29	10.54	0.02	0.40
	Total	-472.73	118.11	0.61	24.95**	-78.79	17.64	0.10	1.76

† m = g ppm^{-1}.

†† b = g.

Regression analyses that give F-ratios greater than the tabulated values for the F-distribution at α = 0.10, α = 0.05, and α = 0.01 are denoted by †, *, and **, respectively.

TABLE 4.4.2.4. PERCENT REDUCTION IN LEAF, STEM, ROOT, AND TOTAL DRY WEIGHT OF SOYBEAN, MAINTAINED ON TWO WATERING REGIMES DUE TO EXPOSURE TO O_3 FOR 2, 4, 6, OR 8 WEEKS. [PERCENT REDUCTION CALCULATED FROM REGRESSION EQUATIONS WITH 100% SET AT VALUE ESTIMATED AT 0.025 PPM O_3.]

		% Reduction (Biomass = 100% at 0.025 ppm O_3)					
		Well Watered			Water Stressed		
Harvest	Dry Weight	0.05	0.09	0.13	0.05	0.09	0.13
1	Leaf	9	24	38	9	23	37
	Stem	8	22	35	8	21	33
	Root	6	14	23	9	23	37
	Total	7	19	31	9	22	36
2	Leaf	10	26	41	5	14	22
	Stem	10	25	41	4	11	18
	Root	7	19	31	6	14	25
	Total	9	24	39	5	13	22
3	Leaf	13	35	56	10	25	41
	Stem	13	33	53	9	23	37
	Root	13	34	55	10	25	40
	Total	13	34	55	9	24	39
2	Leaf	14	35	57	6	16	25
	Stem	10	26	42	6	14	23
	Root	10	26	42	5	13	21
	Total	11	29	47	6	14	23

reductions due to O_3 were greater in the well watered plants. For example, at harvest 3 0.05 ppm O_3 caused a 13% reduction in total dry weight in the well watered plants and only a 9% reduction in the water stressed plants, while the estimated reductions with 0.13 ppm O_3 were about 55% for the well watered plants and only 40% for the water stressed ones.

Effect of O_3 on flowering. Plants exposed to 0.13 ppm O_3 started to flower an average of seven days later than those exposed to 0.01 ppm (Figure 4.4.2.3). In addition, plants exposed to 0.01 ppm initially flowered at node 6, while those exposed to 0.13 ppm initially flowered at nodes 9 or 10.

Leaf CO_2 exchange. The effect of leaf aging on the rate of photosynthesis (P_n) was typical; P_n increased rapidly in developing leaves and declined gradually with increasing leaf age (Figure 4.4.2.4). This pattern was observed for plants in all O_3 treatments. However, photosynthetic rates were consistently depressed, over all leaf ages, in leaves exposed to elevated O_3 concentrations (Figure 4.4.2.4). These reductions were roughly linear with increasing O_3 concentration. Leaves which had been unfolded for as little as one day had reductions in P_n corresponding to their O_3 treatments. As leaves aged, the differences in P_n among the O_3 treatments continued to grow larger until leaves were 9-12 days old. As leaves aged from 12-22 days, P_n differences among treatments appeared to narrow. A word of caution should be made concerning this latter trend. All measurements of P_n were made on green, healthy-looking, nonsenescent leaves. However, many of the 15-20 d old leaves in the two higher O_3 treatments were chlorotic and senescent, and therefore were not selected for measurements. Consequently, the P_n values observed for older leaves in these two treatments may not have been representative of the P_n of the average leaf of that age in those treatments.

Dark respiration rates were always low (0-2 mg dm^{-2} h^{-1}) and no differences among O_3 treatments were observed, regardless of leaf age (data not shown).

Whole plant CO_2 exchange. Chronic exposure to increasing O_3 concentrations resulted in a linear decline in whole plant P_n, and plants exposed to 0.13 ppm O_3 experienced a reduction in P_n of 22% compared with control plants. Whole plants had populations of leaves of all ages and although incident photosynthetically acive radiation at the top of the canopy was similar to levels for individual leaves in which CO_2 exchange was measured, significant self-shading occurred. Both of these factors contributed to P_n in whole plants being much less than P_n reported in 6-16 day old leaves of similar treatments. No effects of O_3 treatments were detected on dark respiration rates in whole plants.

Net assimilation rates (NAR) were calculated for each O_3 treatment throughout the experiment (Table 4.4.2.5). Comparison of NAR with P_n for whole plants (well watered) shows that relative effects of treatments were extremely similar on both measures of plant response. This indicates that measurement of P_n with the CSTRs was an accurate means of assessing whole plant photosynthetic response.

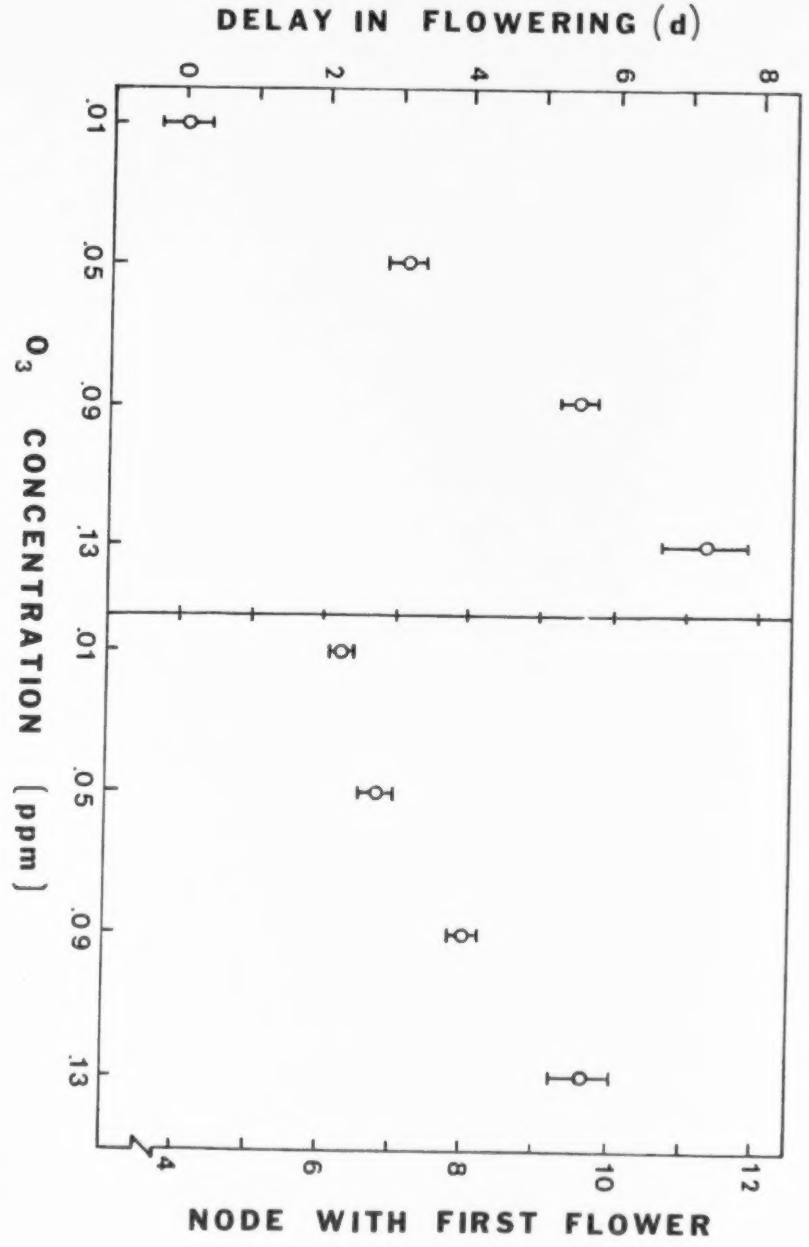

Figure 4.4.2.3. Effect of O$_3$ on date of first flower and node at which first flower developed.

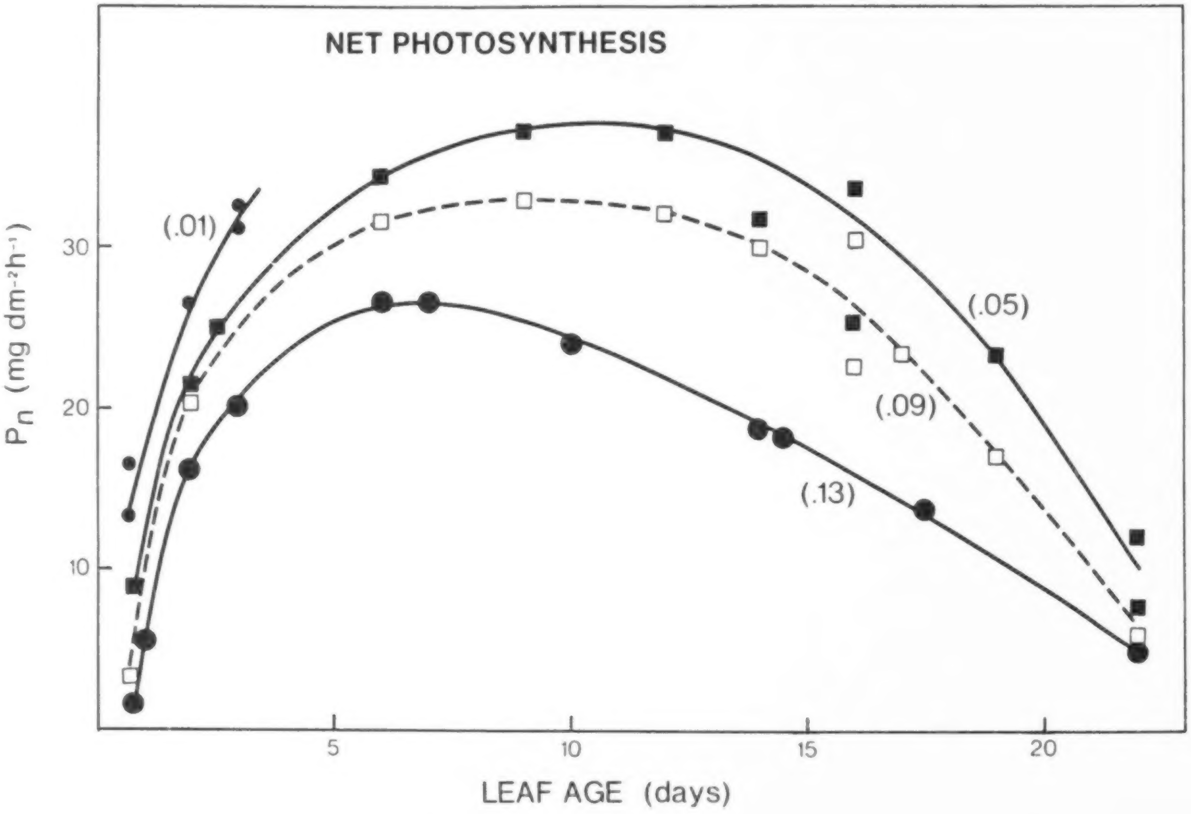

Figure 4.4.2.4. Effect of O_3 (0.01, 0.05, 0.09, or 0.13 ppm) and leaf age on net photosynthesis (P_n) of individual soybean leaves.

TABLE 4.4.2.5. EFFECT OF O_3 TREATMENT ON NET ASSIMILATION RATES (NAR) AND WHOLE PLANT PHOTOSYNTHESIS (P_n).

O_3 Treatment (ppm)	% of Control		
	Well Watered		Water Stressed
	NAR*	P_n (CSTR)**	NAR*
0.01	100	100	100
0.05	91	91	80
0.09	88	90	83
0.13	74	78	82

* Calculated according to Woodruff (1969) from growth data.

** Monitored on individual plants.

Leaf Chl contents and relationship to P_n. O_3 treatment and leaf age both influenced leaf chlorophyll (Chl) contents. Chl a, Chl b, and Chl a + b contents displayed the typical age-related pattern (increasing in young leaves and decreasing in aging leaves) in all treatments regardless of plant age or duration of O_3 exposures. Exposure to increasing O_3 concentrations consistently resulted in large decreases in Chl contents of leaves 12 d or or older regardless of whether plants had been exposed to O_3 for 4, 6, or 8 weeks. Among 3-7 d old leaves, the same effect was generaly observed but to a lesser extent than with older leaves.

Mean Chl a + b contents per plant, on a unit leaf area basis, were linearly reduced by exposure to increasing concentrations of O_3 (Figure 4.4.2.5). Also, the percent reduction in Chl a + b due to exposure to 0.13 versus 0.05 ppm O_3 grew from 16 to 37 to 47% following 4, 6, and 8 weeks of exposure, respectively (Figure 4.4.2.5). Furthermore, the Chl a + b contents of either individual leaves or per plant were linearly related to P_n in either leaves or whole plants.

Stomatal conductance and water use efficiency. Analysis of variance of stomatal conductance data found no significant interactions among O_3 treatments, watering treatments, and/or leaf age. Thus, analysis of these factors alone could be done using pooled data from all treatments, and all three factors did influence stomatal conductance (Figures 4.4.2.6). A reduced water supply resulted in low abaxial (k_{ab}) and total (k_t) conductance at any age, but did not affect adaxial conductances (k_{ad}) (Figure 4.4.2.6). Also apparent in Figure 4.4.2.6 are the different effects of leaf age on k_{ab} and k_{ad}. Adaxial conductance in both well watered and droughted plants decreased linearly with increasing leaf age. In contrast, k_{ab} in both watering treatments increased with age from 2-6 to 7-11 days of age, and then decreased with increasing age.

Regardless of leaf age, exposure to increasing O_3 concentration was linearly related to decreasing k_{ab}, k_{ad}, and k_t, except for k_{ad} in middle-aged leaves. The effect of exposure to O_3 was roughly similar for conductance of both leaf surfaces on a relative percentage basis. Exposure to O_3 also resulted in a linear decline in water use efficiency of whole plants (Figure 4.4.2.7).

4.4.2.4 Discussion

Effects of water stress. As previously shown for field grown soybeans (Momem *et al.*, 1979), water stress greatly reduced plant growth. Although the water stressed plants were smaller than the well watered plants, the percent of total biomass distributed to roots, stems, or leaves was not altered, nor was the time of flowering. O_3 reduced growth more in the well watered plants than in the water stressed plants most, likely as a result of more O_3 uptake in the well watered plants due to higher stomatal condutances. The effect of water stress on the net assimilation rates of the soybeans was assumed to be caused by a direct effect on net photosynthesis; however, it is a circular argument whether the reduced stomatal conductances of these plants are the result of reduced photosynthetic rates or the case of reduced P_n by stomatal closure directly attributable to water stress (see Farquhar and Sharkey, 1982, for a current review).

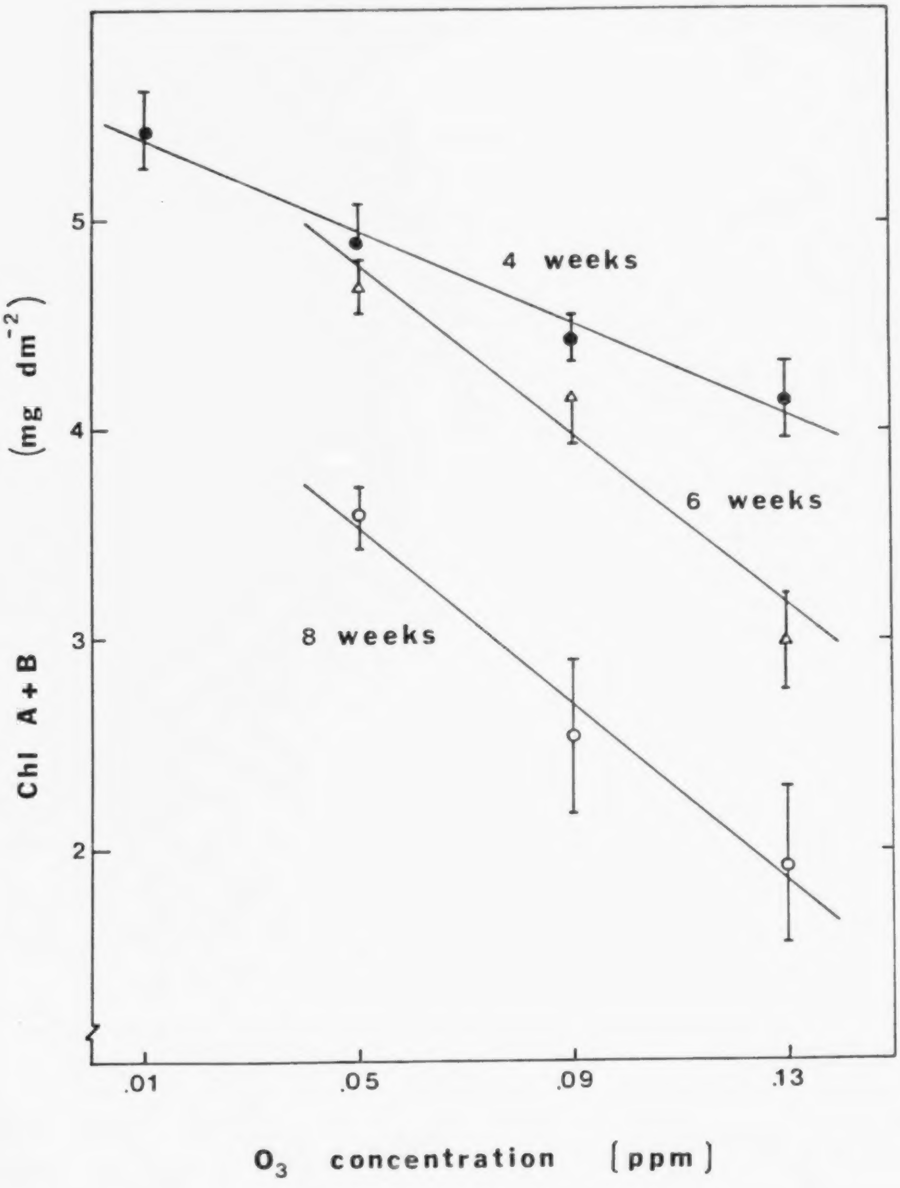

Figure 4.4.2.5. Chlorophyll content of soybean leaves from plants exposed for 4, 6, or 8 weeks to 0.01, 0.05, 0.09, or 0.13 ppm O_3.

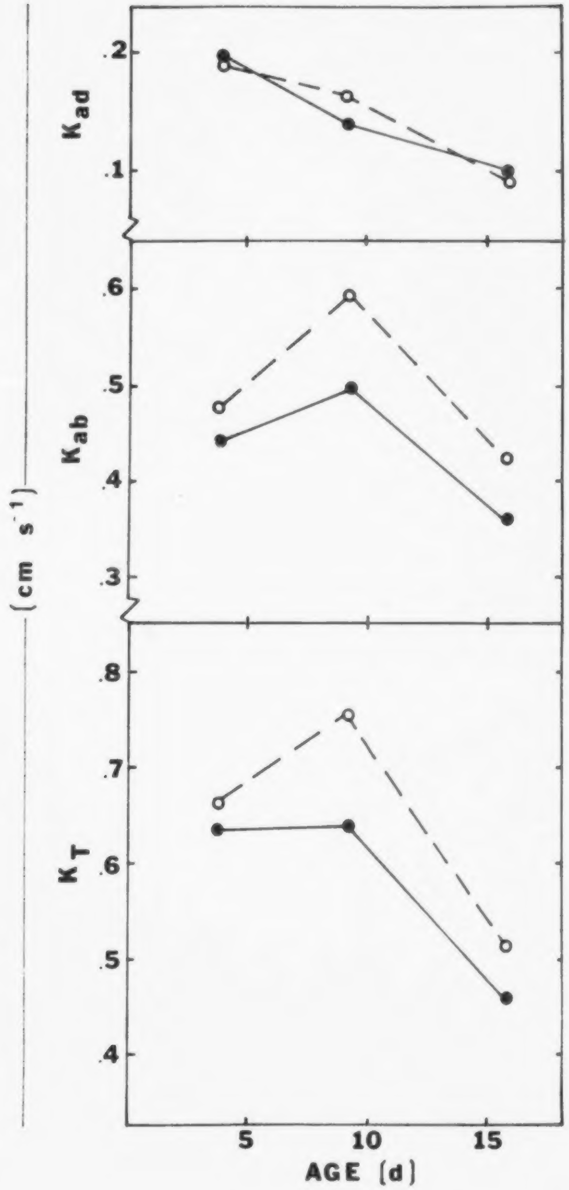

Figure 4.4.2.6. Effect of watering regime and leaf age on stomatal conductances of soybean (k_{ad}, adaxial surface; k_{ab}, abaxial surface; k_t, total leaf surface). Dotted line = wet, solid line = dry.

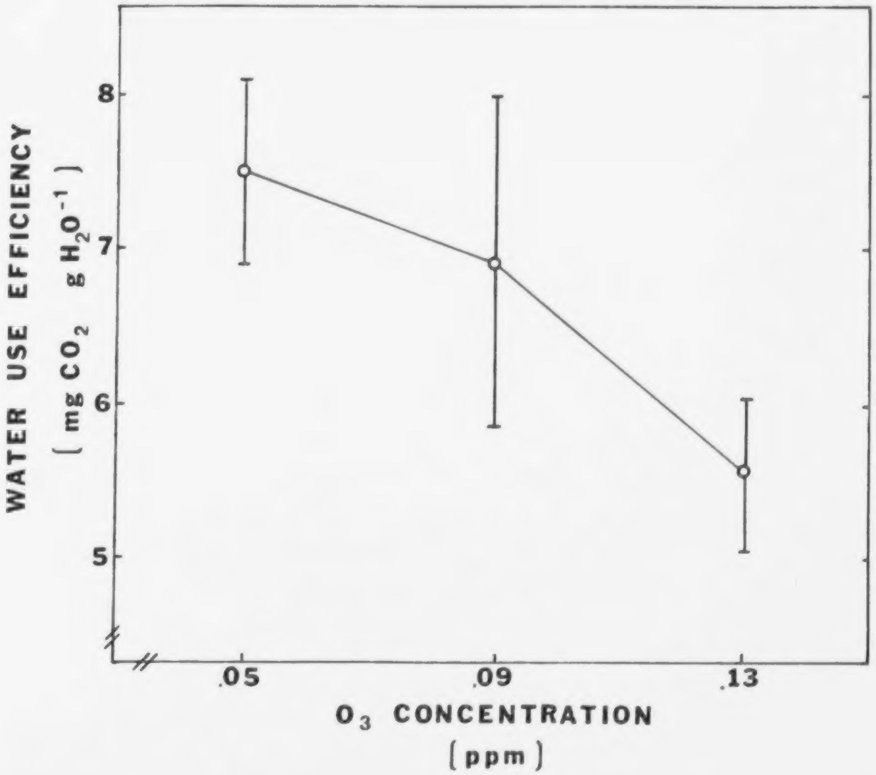

Figure 4.4.2.7. Effect of O_3 concentrations on soybean water use efficiency (defined as mg CO_2 fixed per g of H_2O transpired).

Effects of O_3 stress. Exposure to increasing concentrations of O_3 produced linear reductions in all growth variables measured for the well watered plants, which is in agreement with the results of studies on field grown Hodgson soybeans. These reductions in plant biomass of field grown soybeans were correlated with reductions in yield. In contrast to findings in this study, the delay in flowering due to O_3 was not found in a field test with 'Davis' soybeans (Heagle, personal communication).

Chronic exposure to increasing concentrations of O_3 resulted in linear reductions in P_n and Chl contents of either individual leaves or whole plants. This suggests that the O_3 is acting directly on the photosynthetic process and that differences in soybean P_n between treatments were not likely the result of O_3-induced stomatal closure. Age-related changes in P_n and leaf Chl contents in all treatments were relatively typical (Reich, 1983).

How many hours or days of O_3 exposure are needed to influence P_n, or are such effects instantaneous? Leaves which had been unfolded for as little as one day had reductions in P_n which were related to O_3 treatments. However, it should be noted that cells in expanding leaves which had been unfolded for one day had been exposed to O_3 for a number of days prior to and during unfolding and that the plants had been exposed for at least two weeks before the P_n measurements were started. Also, exposure to O_3 had no immediate or short term (less than a day) effect on CO_2 exchange; P_n remained stable following step changes in O_3 concentration between 0.01 and 0.13 ppm, regardless of leaf age, previous treatment, or direction of step change (data not shown).

Decreases in P_n following chronic exposure to low concentrations of O_3 have been observed in a number of other species. In our laboratory, recent studies with hybrid poplar (Reich, 1983) and sugar maple (Reich _et al._, unpublished data) found significant decreases in P_n of plants exposed to either 0.09 or 0.13 ppm O_3. Miller _et al._ (9) found significant declines in P_n of ponderosa pine seedlings treated for 60 days (9 h d^{-1}) with 0.15 ppm O_3 and Ormrod _et al._ (12) observed decreased P_n in _Vicia faba_ exposed to O_3 concentrations as low as 0.10 ppm.

The O_3-induced reductions in P_n of Hodgson soybean were consistent with observed reductions in NAR, growth, and dry mass accumulation. In addition, the effects of O_3 and water stress alone on soybean growth were similar to responses recorded for field grown soybeans (Kohut and Amundson, unpublished; Momen _et al._, 1979), respectively. Therefore we think that the enhanced effect of O_3 on water stressed plants observed in the laboratory should occur under field conditions. Of course, these data cannot be extrapolated to plants grown under extreme environmental or edaphic conditions (e.g., temperature, flooding, soil nutrition, pests, and pathogens) since these factors might alter or negate any O_3-water stress interaction.

4.4.2.5 Conclusions

Exposure to increasing concentrations of O_3 produced linear reductions in soybean biomass in both well watered and water stressed plants. However, the percent reductions in biomass due to O_3 were greater in the well watered soybeans. O_3 also accelerated leaf aging, delayed onset of flowering, reduced chlorophyll content of leaves, and reduced net photosynthesis of individual leaves and whole plants; this series of effects helps explain the reduced net assimilation rates of whole plants exposed to the higher concentrations of O_3 and the reduced numbers of pods per plant and the reduced weights per pod on the plants at the final harvest (growth stage R4). All of these effects of O_3 on soybean productivity help to explain the yield reduction found previously in field grown and exposed plants. The reduced effect of O_3 on the water stressed soybean suggests that dose-response equations derived from well watered plants will overestimate the yield losses of soybeans subjected to water stress.

4.4.3 Response of Cotton Yields to O_3 as Mediated by Soil Moisture (SWRCLAP -- Shafter, California)*

4.4.3.1 Introduction

Acala SJ-2 is the most widely planted cultivar of cotton in California, covering about 75% of the 1.6 million acres of irrigated cotton cropland in the state. Results of a dose-reponse study conducted in 1981 at Shafter indicated that, under typical summer growing conditions and normal irrigation, exposure to ambient O_3 in chambers reduced lint yields in this variety by 20% relative to yields in charcoal-filtered chambers. Yields were reduced 58% at the highest O_3 concentraions. Plants subjected to severe water stress had lower yield than normally irrigated plants and showed comparatively little response to O_3. The objective of the 1982 experiment was to repeat this study for a second year, to compare responses of normally irrigated and water stressed cotton to a range of O_3 doses under varying climatic conditions.

4.4.3.2 Materials and Methods

Cultural. The 1982 experiment was conducted again at the USDA Cotton Research Station in Shafter. The soil is a deep Wasco sandy loam (coarse-loamy, mixed non-acid, thermic, Xeric Torriorthents) with some variation in percent sand. Pre- and post-season soil sampling indicated that measured parameters were within optimal range for cotton production.

Pre-emergence herbicide (Treflan, 0.6 kg/ha) was applied on April 4, and the field was bedded up on 102 cm centers. Pre-planting irrigation was completed on April 9, with soil moisture at field capacity to a depth of 1.7 m. Acala SJ-2 cotton (*Gossypium hirsutum* L.) was planted on April 21 in three strips of six east-west rows 102 cm apart with 2 m of access between each strip. Emergence began on April 26, and the site was mechanically cultivated and side-dressed with the standard fertilizer appliation of 67 kg/ha of 21-10-0 (N-P-K) on May 20.

Ten plots in each of the 3 strips were marked off on 7.6 m centers. Each plot contained 6 rows of cotton 6.1 m long. Twenty-four cylindrical open-top chambers [3 m in diameter, 2.4 m high, equipped with cone tops (frusta) that restricted top opening to 1.94 m] were centered on randomly selected plots on May 28, and four additional plots were selected as ambient (nonchamber) controls. Chambers were positioned over two center sample rows, leaving two guard rows on each side of the chamber. The fifth row from the north in each plot was designated as the companion row. Open plot sample rows and companion rows were similarly marked. Sample and companion rows in all plots were thinned on June 12-16 to 16 plants per sample row (6 ± 1 plants per m-row), giving an estimated plant density of 53,000/ha. Details of pesticide applications and other cultural practices are given in Table 4.4.3.1.

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* O. C. Taylor, P. J. Temple, L. F. Benoit, C. Reagen, R. W. Lennox.

Irrigation. Plots were assigned at random to normal irrigation or water stressed treatments. Each plot was individually diked and irrigated through a PVC manifold that delivered water to each furrow at a constant rate of 25.4 mm per hour of irrigation. Sections of 76 mm PVC drain pipe in furrow bottoms under chamber walls allows irrigation water to flow through the chambers. Soil tensiometers (Irrometer Company, Riverside, California) were calibrated at saturation and installed in each sample row at a depth of 46 cm and at a distance of 46 cm from the west end of each chamber and open plot. Tensio meters were read between 0600 and 0900 PDT with readings clustered near the beginning and end of the 8 to 10 day irrigation interval. Irrigation scheduling was based primarily on leaf xylem water potential. Pressure bomb measurements (Plant Water Status Console, Model 3000, Soil Moisture Equipment Corporation, Santa Barbara, California) were taken on uppermost 3/4 to fully-expanded leaves from 1 to 3 nonsample plants in each chamber or outside plot. All measurements were made within 3 hours of solar noon near the beginning and end of the irrigation cycle. Each plot was watered individually. Normally irrigated plots received 76 mm of water when average xylem pressure potential reached -18 bars (-1.8 MPa). Water stressed plots received 64 mm of water when xylem pressure potentials reached -20 bars (-2.0 MPa). In 1981, water stressed plants were irrigated at -21 bars (-2.1 MPa), and the cotton frequently wilted in late morning or early afternoon. In 1982, almost no wilting was observed in water stressed or normally irrigated plots. Total seasonal irrigation in 1982 in the normal plots was 84.6 ± 2.8 cm; water stressed plots received 70.8 ± 2.3 cm of water.

O_3 Treatments and Monitoring. The 24 chambers were assigned at random to 6 O_3 levels with two replicated O_3 treatments per level of soil moisture. O_3 levels were: (1) full charcoal filtration (CF); (2) half charcoal filtration (half-F); (3) no charcoal filtration (NF); (4) NF x 1.3 ambient O_3 concentration; (5) NF x 1.7 of ambient O_3; (6) NF x 2.0 ambient O_3 concentration, as shown in Table 4.4.3.2. O_3 was added from 0900 to 1600 PST daily from June 2 when plants were in 2-3 true leaf stage (20-30 cm in height) to September 9, when ambient concentrations exceeded 0.03 ppm. Concentrations in the O_3-added chambers were controlled by an in-line electronic signal controller (Lawrence Livermore National Laboratory) directed by millivolt output from a Dasibi O_3 analyzer (Model 1003-AH; Dasibi Environmental Corporation, Glendale, California) monitoring ambient O_3 at canopy height in one of the open plots. The controller converted millivolt input to milliamp output signalling the Griffin O_3 generator (Model GTC-1A, Griffin Technics Corporation, Lodi, New Jersey) to modulate voltage, and O_3 output, in response to ambient O_3 concentrations. O_3 flow to each chamber was proportioned through flowmeters (Aalborg FM 112-02; Aalborg Corporation, Monsey, New York), and entered the blower box between dust filter and fan.

Ambient, chamber, and open plot O_3 concentrations were monitored from June 2 to October 19, the day before harvest. Sample air from chambers and plots was collected continuously at 4 l/min from 10 cm above canopy height

TABLE 4.4.3.1. CHRONOLOGY OF SIGNIFICANT EVENTS IN CULTIVATION TREATMENT OF ACALA SJ-2 COTTON AT SHAFTER, CALIFORNIA, 1982.

Month	Day	Event
April	07	Pre-emergent herbicide Treflan applied (0.6 kg/ha) Pre-tilled plot area bedded up
	09	Pre-irrigation completed
	21	Planted cotton 'Acala cv SJ-2'
	26	Plants emerged
May	26	Cotton mechanically cultivated and side dressed with 67 kg/ha of nitrogen at 21-10-0 (N-P-K)
	28	Open-top chamber installed; blowers on 0600-2100 LT
June	01	Irrometers installed
	02	O_3 additions started; plants at 2-3 true leaf state and 20-30 cm in height
	12	Plants thinned to 16 plants/sample row (inside chamber) and companion row
	14	Spot infestations of aphids detected and Malathion 50 (5 ml/gal) used to spot spray throughout rest of season
	17	First O_3 injury (interveinal chlorosis) symptoms noted (high O_3 treatments)
	24	First open bloom
	27	Injury as purple-brown stipple noted in O_3-added treatments
July	11	Premature senescence and defoliation noted in O_3 added-treatments
	12	Altosid (5 ml/gal) sprayed on all plots for aphid and white fly. Kelthane (5 ml/gal) sprayed on all plots for two-spotted mite. Thuricide (4 ml/gal) sprayed on all plots for lepidopterous larvae.
	23	Kelthane (5 ml/gal) sprayed on all plots
August	04	Interveinal chlorosis noted on nonfiltered and open plots
	07	Kelthane (5 ml/gal) sprayed on all plots. Thuricide (4 ml/gal) sprayed on all plots.

(continued)

TABLE 4.4.3.1 (continued)

Month	Day	Event
	12	First open bolls
	19-24	Visual symptom ratings
	30	Analyzer audit
September	08	Altosoid (5 ml/gal) sprayed on all rows outside chambers. Thuricide (4 ml/gal) sprayed on all rows outside chambers.
	09	Last day of O_3 additions
October	19	Top panels removed
	20	First pick harvest, chambers
	21	First pick harvest, companion rows
November	15	Second pick harvest

TABLE 4.4.3.2. SUMMARY OF O_3 CONCENTRATIONS DURING EXPOSURE OF 'ACALA SJ-2' AT SHAFTER, CALIFORNIA, JUNE 4 TO OCTOBER 19, 1982. ALL DATA IN ppm.

Treatment*	Seasonal 7-h Mean (June 2-Oct 19)**	Seasonal 7-h Mean (June 2-Sept 9)†	Highest 1-h Peak	Highest 7-h Day	Mean Max. Hourly Ave.
CF	0.012	0.012	0.027	0.024	0.016
Half-F	0.031	0.033	0.057	0.048	0.039
NF	0.045	0.047	0.081	0.068	0.055
NF x 1.3	0.065	0.075	0.142	0.124	0.080
NF x 1.7	0.077	0.092	0.185	0.152	0.095
NF x 2.0	0.092	0.114	0.209	0.182	0.113

* CF = charcoal filtered; half-F = half filtered; NF = nonfiltered (ambient); NF x 1.3, 1.7, 2.0 = nonfiltered plus 1.3, 1.7, 2.0 x ambient O_3 concentration, respectively.

** Monitoring season.

† O_3 dispensing season.

through individually dust-filtered Teflon lines 45.7 m long. The lines merged at dual 12-port rotary sample valves (Scanivalve Corporation, San Diego, California) which rotated to the next port every two minutes, so that every sample line was monitored for a total of 5 minutes every hour. The two Dasibi O_3 analyzers monitoring chamber concentrations and the Dasibi monitoring ambient O_3 were calibrated against a fourth Dasibi designated as a transfer standard calibrated at Haagen-Smit Laboratories, El Monte, California. Ambient sulfur dioxide was monitored by a Monitor Labs Model 8850 SO_2 Analyzer (Monitor Labs, Inc., San Diego, California). All standard protocols regarding quality assurance of instrumentation and line loss checks were made at required intervals. Data from air quality instruments were logged by a TRS-80 Model II microcomputer (Tandy Corporation, Fort Worth, Texas). Interface with the computer was through a REMDACS Analog Remote Station (Intersil Corporation, Cupertino, California) and a REMDACS motherboard (REM MBA204; Intersil, Cupertino, California).

Measurements of Plant Response. Visible Injury -- Visual symptoms of foliar injury were noted as they developed during the season in chambers and ambient plots. Final injury ratings were assessed on August 19 to 24 by noting symptoms on main stem leaves of the fourth or fifth plant from each end of the two sample rows in each plot. Petiole scars and the number of remaining leaves were counted. Typical O_3 injury symptoms (purple-brown stipple, upper-surface or bifacial necrosis, general or interveinal chlorosis) were distinguished from lesions induced by biotic agents (mites, etc.), and percent foliar injury was visually estimated at 10 percent increments for each category.

Stomatal Responses -- Stomatal conductance and transpiration measurements were taken at monthly intervals during the exposure period. Charcoal filtered, NF, and NF x 2.0 chambers, and ambient air (AA) open plots at both levels of soil moisture were sampled between 1030-1230 PST to establish maximum stomtal conductance for each treatment. Five plants were selected at random within each chamber or plot and conductance and transpiration were measured on abaxial surfaces of the highest fully-expanded uninjured leaves of each plant using a steady-state porometer (Model LI-1600, LI-COR, Inc., Lincoln, Nebraska). Simutaneous measurements were taken on light intensity, relative humidity, leaf, and chamber temperatures. On September 2, measurements were made from 0630 to 1930 PST to determine the complete diurnal stomatal responses of these 4 treatments. All plots had been irrigated 6 to 8 days previously.

A shading experiment was conducted on September 3 to compare stomatal response to sudden changes in light intensity in normally irrigated plants growing in CF and NF x 2.0 chambers. This experiment was designed to determine if the lower stomatal conductance observed in plants in NF x 2.0 treatments were due to an impaired stomatal mechanism which inhibited full opening or to indirect effects such as inhibition of photosynthesis by O_3. At 0915, the south rows of each chamber were shaded by double layers of 75% shade cloth, and measurements of stomatal conductance, transpiration, and light intensity were made at 15-minute intervals on five plants in both shaded sout rows and unshaded north rows. Measurements were made as previously described. Shading was removed after 2 h, and stomatal reopening was monitored for an additional hour.

Harvest -- Sample rows in chamber and outside plots were harvested on October 20. Open bolls were collected from 4 separate 1-m sections of the two center rows of each chamber or plot. Data were collected on numbers of open and green bolls and numbers of plants in each section. Companion row plants were sampled on October 21, by harvesting 4 separate 1-m sections from each row. Field weight of open boll samples was determined within a few hours of picking. Samples were weighed on a digital balance (Mettler PC-16, Mettler Instrument Corporation, Highstown, New Jersey) calibrated against a set of standard weights before, during, and after each weighing period. A second pick of open bolls on November 15 added very few additional mature bolls to previous samples. First and second pick samples were combined and ginned at 5.5 percent moisture on a portable (Ten Saw) gin. Pre-gin bulk weight and lint and weed weights were measured for each sample, as above. Fiber quality was determined for random subsamples from each plot at the fiber laboratory, USDA Cotton Research Station, and classification was performed at the USDA Cotton Marketing Service, Bakersfield, California.

Data Analysis -- Companion plot data were analyzed for systematic trends across the field, but none were detected. Analysis of covarance using companion plot data did not significantly improve goodness-of-fit of regression models. Thus, companion plot data were not included in final regression analyses. Harvest data from chambers were analyzed as a split-plot factorial experiment with 6 levels of O_3 and 2 levels of soil moisture as whole plot effects and position in chamber (2 north/south samples and 2 east/west samples) as subplot effects. Dose-response curves were fit to individual chamber data by step-up multiple regression analysis using linear, polynomial, and exponential models.

4.4.3.3 Results

Air Quality and Meteorology. Daily weather data obtained from the meteorological station operated at the USDA Cotton Research Station indicated that 1982 growing conditions were unusually cool and humid for the Central Valley of California, particularly in comparison with 1981. Accumulated degree-days above 15.5°C totaled 2713 during the 1981 growing season and 2267 in 1982, a 20% reduction. Monthly average pan evaporation (potential evaporation demand, ET_o) was also about 20% lower in 1982, particularly during June, July, and August (Table 4.4.3.3). These growing conditions also produced atypical crop development. Boll set was unusually early, and the first four weeks of flowering produced 93% of final yield, compared with 58 percent historically (Thomas A. Kerby, Extension Cotton Specialist, University of California). Final yields in 1982 were about the same as in 1981, both on the experimental site and at the USDA Cotton Research Station.

O_3 concentrations were also lower in 1982 than in 1981. Seasonal 7-h (0900-1600 PDT) mean ambient O_3 concentration for the sampling period June 2 to October 19, 1982, was 0.047 ppm. Seasonal 7-h means for the 6 chamber treatments were, in ascending order, 0.012, 0.031, 0.045, 0.065, 0.077, and 0.092 ppm. Other measures of O_3 exposure, including highest 1-h peak, highest 7-h day, and seasonal mean maximum hourly average are given in Table 4.4.3.2. Fluctuations in daily 7- and 24-h ambient O_3 concentrations are shown in Figure 4.4.3.1. Seasonal average diurnal curves of O_3 concentration for chambers and open plots are shown in Figure 4.4.3.2. Ambient SO_2 measurements were at or close to zero for the entire sampling period.

TABLE 4.4.3.3. MONTHLY AVERAGE PAN EVAPORATION (mm/day) AT USDA COTTON EXPERIMENT STATION, SHAFTER, CALIFORNIA.

Month	1981	1982	Average 1975-1980
April	5.11	5.20	6.04
May	7.96	8.62	9.21
June	10.19	8.42	10.02
July	10.05	8.04	8.65
August	8.18	6.73	7.23
September	6.70	5.04	6.25
October	3.90	3.74	4.23

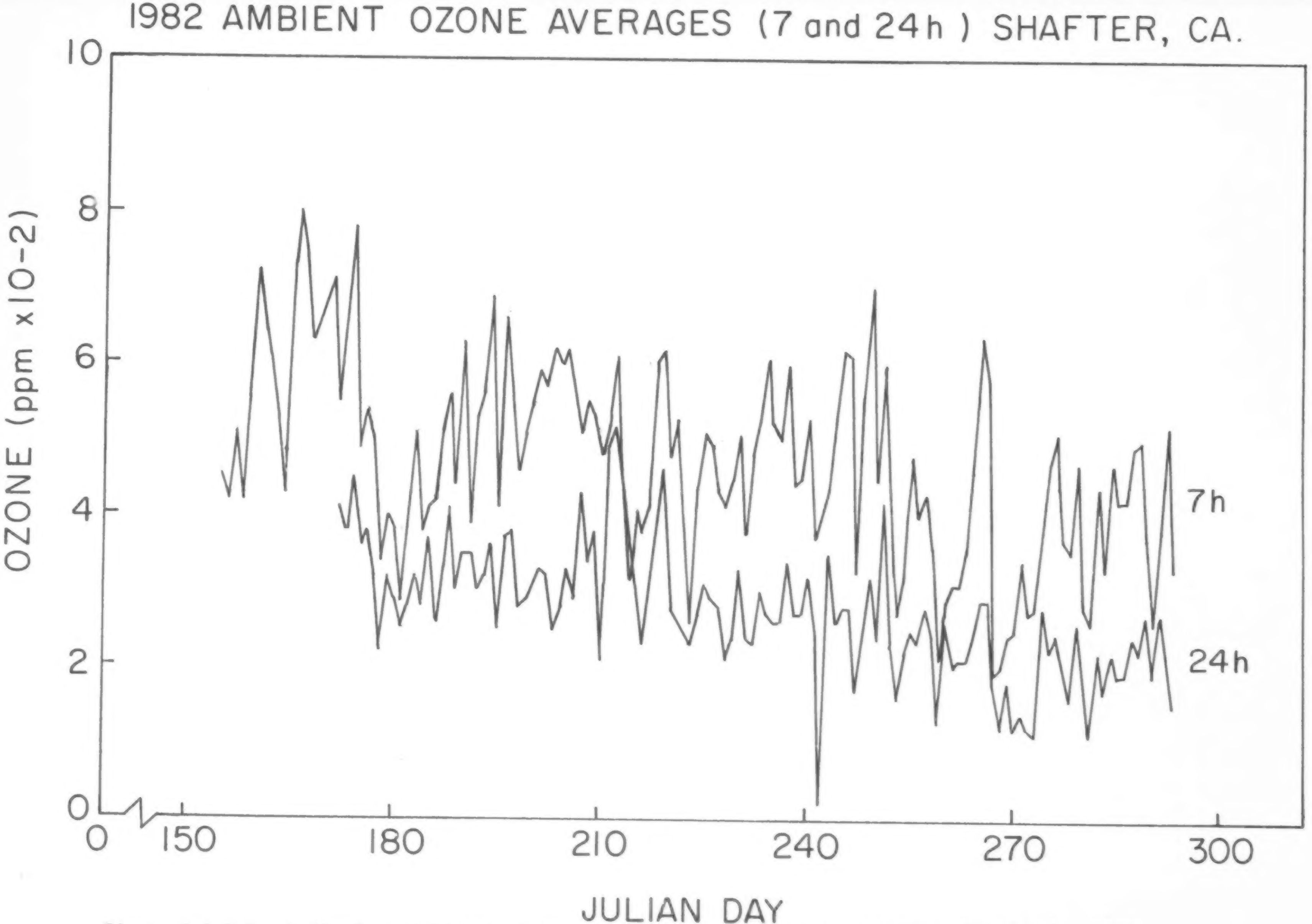


Figure 4.4.3.1. Daily 7- and 24-h average ambient O_3 concentrations, Shafter, California, 1982.

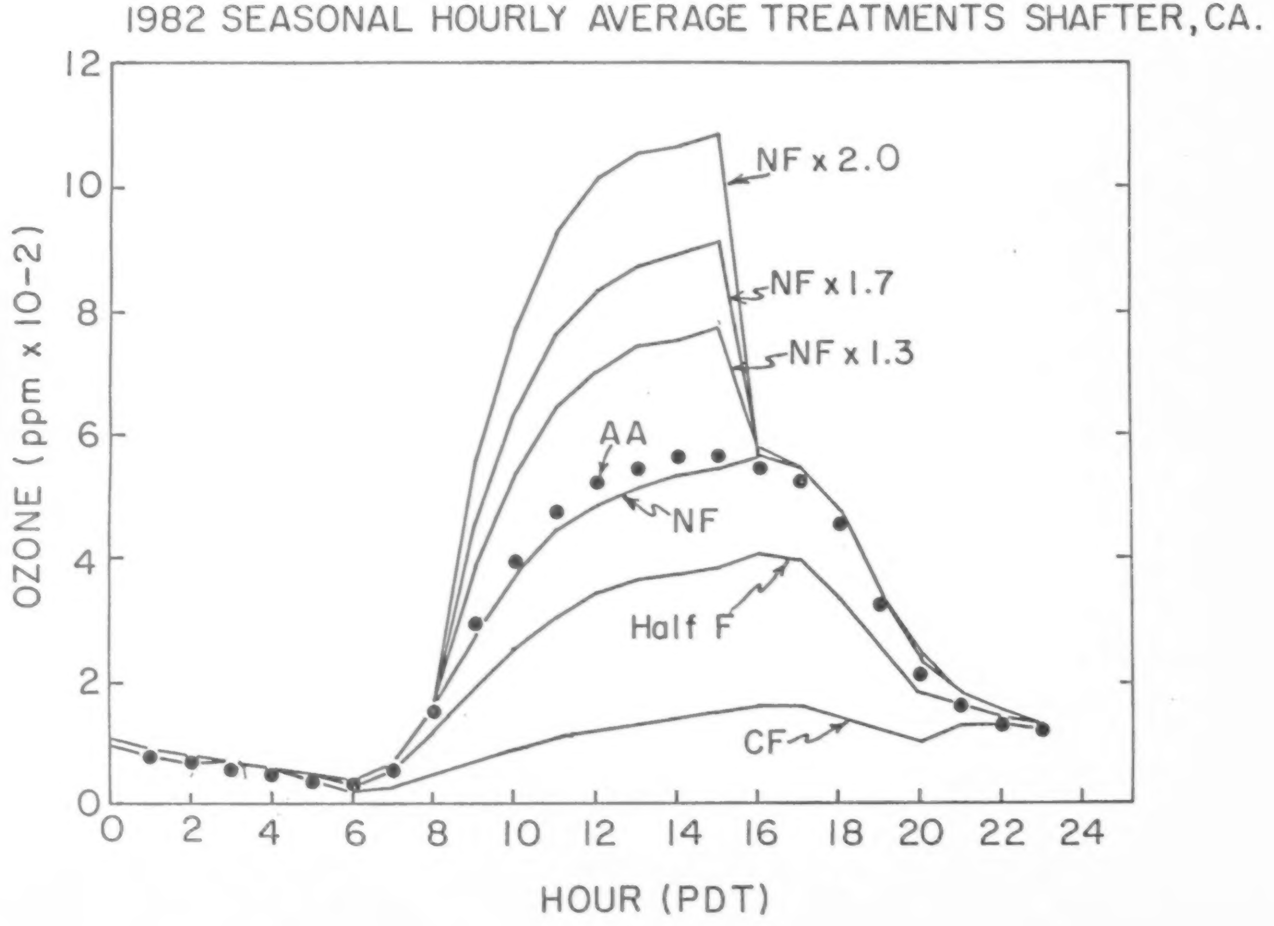


Figure 4.4.3.2. Diurnal curves of seasonal mean hourly O_3 concentrations for each treatment, Shafter, California, 1982.

Plant Responses. Foliar Injury -- O_3 injury symptoms (interveinal chlorosis) were noted first in NF x 2.0 chambers on June 17, 2 weeks after start of O_3 additions. Purple-brown stipple on adaxial foliar surfaces was noted in O_3-added treatments on June 27. Premature senescence and abscission of lower leaves was first observed in O_3-added treatments on July 11. Plants in ambient chambers and open plots had developed interveinal chlorosis by August 4. Final injury ratings are given in Table 4.4.3.4. Differences in foliar injury between normal and water stresed plants were not significant. Correlation between foliar and seasonal 7-h O_3 concentrations was highly significant ($r = 0.96$; $p < 0.01$), as was correlation between injury and lint yield ($r = -0.92$; $p < 0.01$). Foliar injury in 1982 was significantly higher in open plots and in ambient and filtered chambers compared with 1981. Injury in O_3-added treatments was slightly higher in 1982 than in 1981.

Stomatal Responses -- Diurnal curves of stomatal conductance and transpiration are shown for normally irrigated plots in Figure 4.4.3.3. Measurements were made on September 2, a "typical" summer day in Shafter on which temperature reached 38°C and RH was between 20-30%. Stomata were fully open by 0900-1000 PDT. They began closing around 1500 and were generally closed by 1800. Stomatal conductance was most highly correlated with light intensity, which also peaked at 1300 PDT. Transpiration rate peaked later in the day and remained high later in the day than conductance. Rate of transpiration was most highly correlated with vapor pressure deficit. Plants in open plots and in CF and NF chambers showed similar responses. However, plants in NF x 2.0 chambers had significantly lower conductance and transpiration than plants in other treatments. Maximum stomatal conductance in these plants averaged only half that of other treatments, and transpiration averaged 38% lower. Diurnal curves of conductance and transpiration for plants in water stressed plots were similar (Figure 4.4.3.4). Stomata remained open and rate of transpiration remained high until 1700-1800 PDT. Maximum conductance in these plots averaged 22% lower than non water stressed plants, but rates of transpiration were about the same as in normally irrigated plots. Plants in the NF x 2.0 treatment had 30% lower maximum stomatal conductance than in other treatments, but transpiration was only about 17% lower.

Results of this shading experiment are shown in Figure 4.4.3.5. Conductance in both CF and NF x 2.0 plants declined rapidly within 15 minutes after 90% shading was applied. Conductance of shaded O_3-stressed plants was significantly lower than that of plants grown in charcoal-filtered air. Stomatal conductance in both treatments increased rapidly to levels of nonshaded plants 30 minutes after shading was removed. The rate of increase of stomatal conductance after removal of shading was the same in both treatments, suggesting that the mechanism of stomatal movement had not been impaired in O_3-stressed plants. These results are consistent with the concept that the primary physiological effect of O_3 is inhibition of photosynthesis, leading to an increase in mesophyll resistance to CO_2. Accumulation of CO_2 mesophyll air spaces has been shown to induce stomatal closure (Meidner and Mansfield, 1968; Hall and Kaufmann, 1975; Hall et al., 1976).

Yield Responses -- Yields of lint and seed of both normally irrigated and water stressed plants were significantly reduced at higher O_3 concentrations (Table 4.4.3.5). Data on number of bolls and weight per boll indicate that yield reduction was attributable primarily to reductions in numbers of open

TABLE 4.4.3.4. PERCENT FOLIAR INJURY OF SJ-2 COTTON AT SHAFTER, CALIFORNIA, AUGUST 21, 1982. RATING SYSTEM IS DESCRIBED IN TEST.

Treatment	% Foliar Reduction	
	Normal Irrigation	Water Stressed
CF	38	41
Half-F	36	44
NF	42	49
NF 1.3	62	66
NF 1.7	71	67
NF 2.0	75	74
Open Plots	56	45

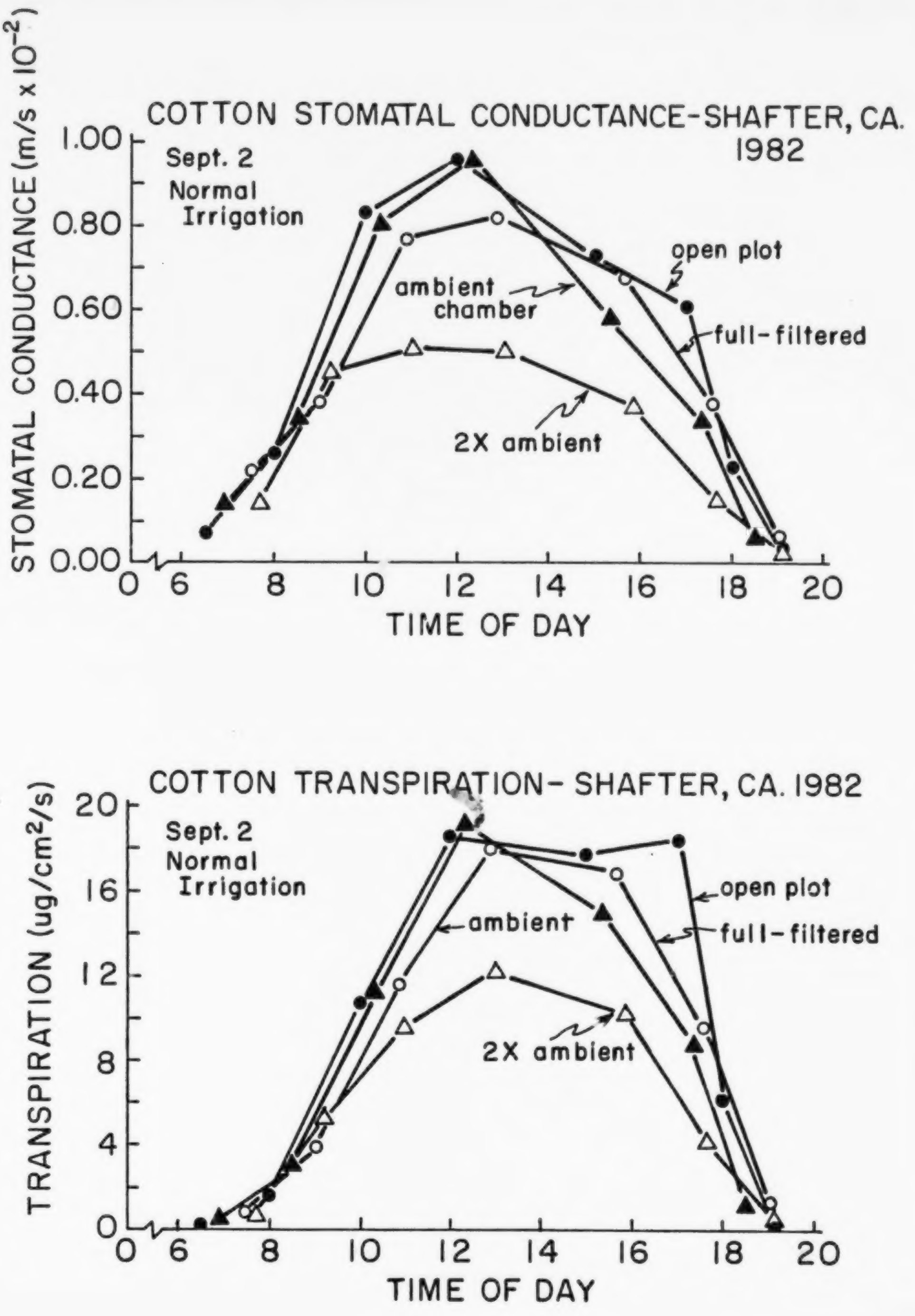
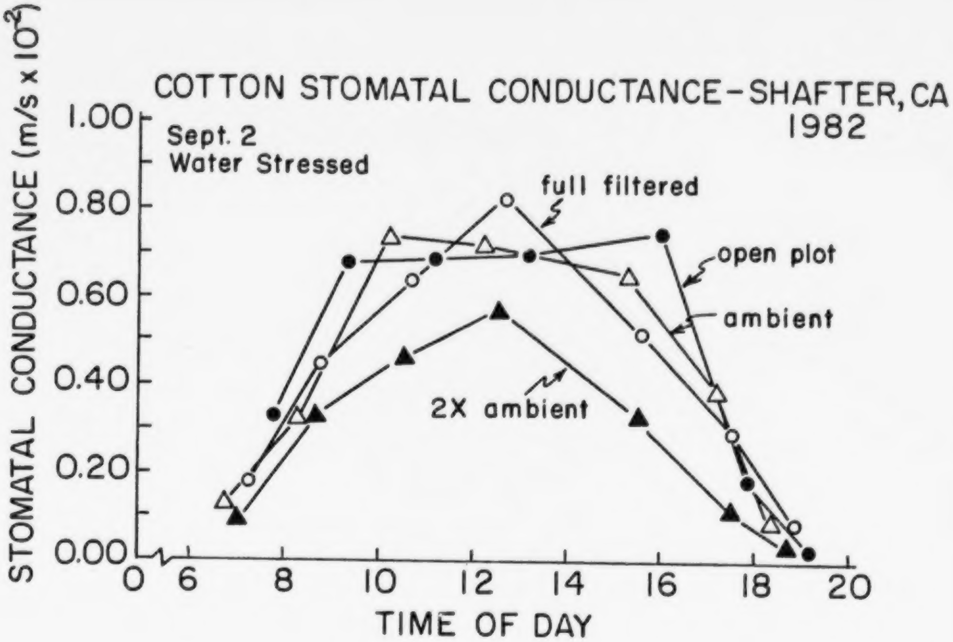


Figure 4.4.3.3. Diurnal curves of abaxial stomatal conductance and transpiration for cotton plants in water stressed plots at Shafter, California. Each point is an average of 5 plants.



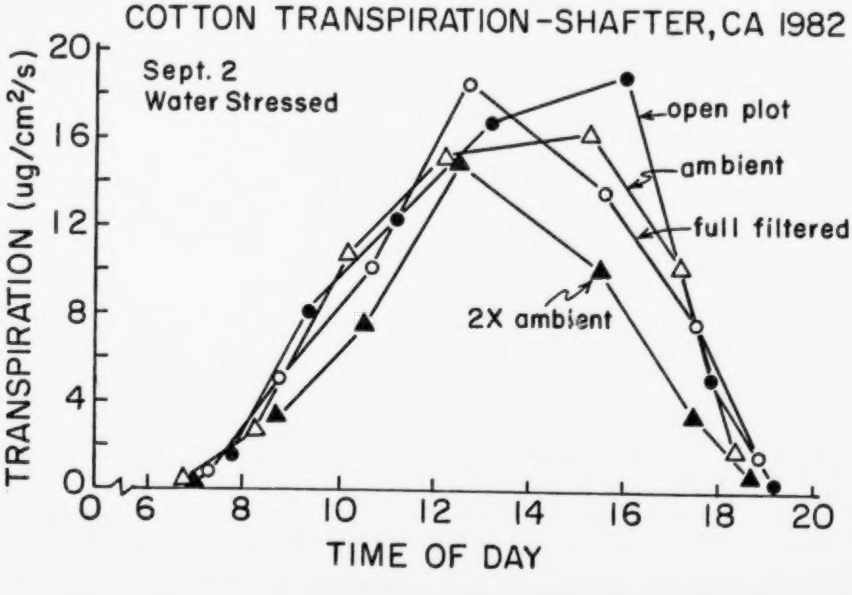


Figure 4.4.3.4. Diurnal curves of abaxial stomatal conductance and transpiration, water stressed plants. Each point is an average of 5 plants.

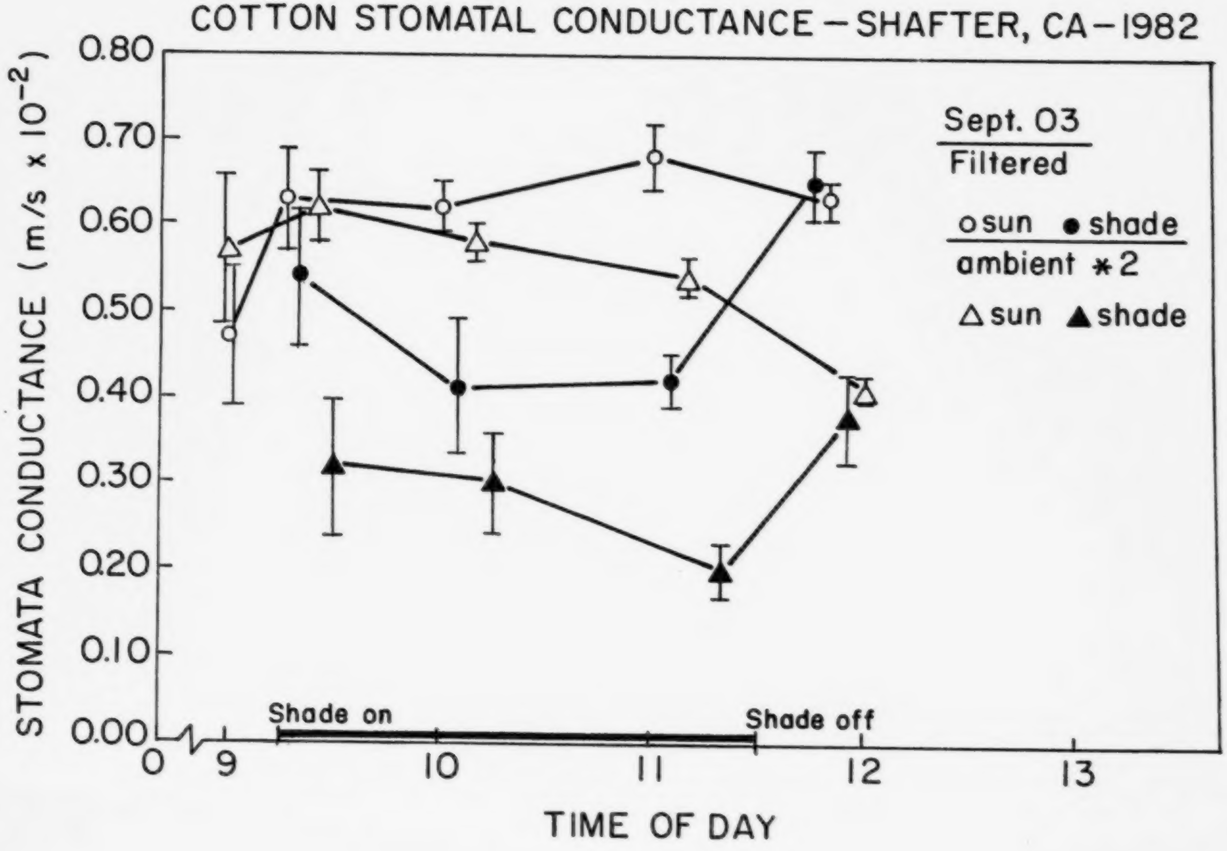


Figure 4.4.3.5. Abaxial stomatal conductance of 90% shaded and nonshaded cotton from normally irrigated plots at Shafter, California. Each point represents an average of 5 plants ± S.E.

TABLE 4.4.3.5. TREATMENT MEANS FOR YIELD PARAMETERS OF SJ-2 COTTON EXPOSED TO O_3 AT SHAFTER, CALIFORNIA, 1982.

		Yield Parameters*				
	Seasonal 7-h Mean Conc. (ppm)	Bulk Wt. of Bolls (g)	Lint Wt. (g)	Seed Wt. (g)	No. Open Bolls	Wt. Per Boll (g)
I. Normal Irrigation						
	0.012	2308	841	1398	356	6.49
	0.031	2314	855	1440	354	6.53
	0.045	1952	715	1221	309	6.34
	0.065	1309	467	831	223	5.82
	0.077	1262	453	802	230	5.51
	0.092	790	288	496	148	5.35
Open**	0.048	2217	828	1368	319	6.96
II. Water Stressed						
	0.012	2012	729	1268	321	6.25
	0.031	1861	685	1168	304	6.11
	0.045	2080	762	1295	322	6.46
	0.065	1452	520	919	255	5.72
	0.077	1118	409	701	219	5.42
	0.092	863	311	513	158	5.46
Open**	0.048	2187	823	1346	312	7.01

* Total of 4 x 1 meter-row samples from each chamber; means of two replicate chambers.

** Outside (chamberless) plots; means of two replicate plots.

bolls rather than in weight per boll. Plants in water stressed plots tended to have lower yield and fewer numbers of bolls, but analysis of variance of harvest data indicated that these differences were not statistically significant (Table 4.4.3.6). Response to O_3 was highly significant ($P < 0.01$), but there was no significant interaction between O_3 and level of moisture. Row position within chambers was also statistically significant; plants in north rows averaged 14% greater yield than those from south rows. East-west orientation within chambers was not significant.

Comparison of open plots with NF chambers indicated that chamber effects reduced yield by about 8%. Number of open bolls inside NF chambers was the same as in chamberless plots, so chamber effects on yield were attributable to an increase in weight per boll in open plots (Table 4.4.3.5). There were no effects on fiber quality in any of the O_3 treatments

Yields in normal and water stressed plots were not statistically different, so data were combined for step-wise multiple linear regression analysis. Best fit regression equations from linear, polynomial, and exponential models are given in Table 4.4.3.7. Regression between square of the mean seasonal 7-h O_3 concentration and yield parameters was highly significant (Figure 4.4.3.6.). Predictions of O_3-induced percentage reduction yield, based on these equations, are given in Table 4.4.3.8. Lint yields in NF chambers were reduced by 15% relative to yields in CF chambers. Yield was reduced 66% at the highest O_3 level.

Differences in response of cotton lint yield to O_3 between 1981 and 1982 are shown in Figure 4.4.3.7. In 1981, yields were severely reduced in plots subjected to water stress and the plants showed comparatively little response to O_3. In 1983, differences in yield between water stressed and normal irrigation plots were slight, and both water regimes showed severe reductions in yield with increasing concentration of O_3. In 1981, exposure to ambient O_3 reduced lint yields by 20% relative to yields in normally irrigated full filtered chambers. Yields were reduced 58% at the highest O_3 concentration (Table 4.4.3.9). In 1982, yields in NF chambers given normal irrigation were 15% less than those in full filtered chambers at an ambient O_3 concentration that averaged 39% less than in 1981.

The greater susceptibility of SJ-2 cotton to O_3 in 1982 was attributed to the cooler, more humid growing conditions that prevailed during the summer. Under conditions of high evaporative demand, as occurred during the summer of 1981, plants were frequently observed to wilt in late morning or early afternoon; stomates closed, and gas exchange was greatly reduced. In 1982, evaporative demand was 20% lower (Table 4.4.3.3); plants rarely wilted and stomates remained open all day (Figures 4.4.3.5 and 4.4.3.6). More O_3 could have entered leaves during mid or late afternoon, when O_3 concentrations were highest. Thus, although concentrations of O_3 were lower in 1982, reductions in yield between the two years were comparable. O_3-added treatments began several weeks earlier in 1982 than in 1981, and this may have contributed to the large reductions in yield observed at the highest O_3 concentrations in 1982.

TABLE 4.4.3.6. ANALYSIS OF VARIANCE MEAN SQUARES FOR YIELD PARAMETERS OF SJ-2 COTTON EXPOSED TO O_3 IN OPEN-TOP CHAMBERS AT SHAFTER, CALIFORNIA, 1982.

Source of Variance	df	Bulk Wt.	Lint Wt.	Seed Wt.	No. Open Bolls	Wt. Per Boll
Block (B)	1	10,209	2,262	1,803	1,785	3,432
O_3 (O)	5	307,782**	42,274**	115,530**	14,291**	33,594**
Irrigation (I)	1	12,558	1,717	3,528	66.7	4,401
O x 1	5	15,296	2,101	5,122	784	2,289
Error†	11	20,927	2,832	7,933	965	3,950
Side (S)†	1	8,513	2,340	5,643	15.04	140
Row (R)‡	1	81,084**	10,086**	22,694**	5,251**	7,176**
S x R	1	10,417	400	8,513	4,520	7,704*
O x S	5	9,218	885	2,349	542	756
O x R	5	3,589	443	661	560	1,025
O x S x R§	5	7,338	949	2,070	404	1,059
Error‡	36	8,785	1,261	2,539	671	1,040

* Significant at 5%; ** 1%.

† East-west orientation in chamber.

‡ North-south orientation in chamber.

§ Other 2-, 3-, and 4-way interactions were tested and were not statistically significant ($p < 0.05$).

TABLE 4.4.3.7. BEST FIT PREDICTION EQUATIONS FOR YIELD PARAMETERS OF SJ-2 COTTON EXPOSED TO O_3 IN OPEN-TOP CHAMBERS AT SHAFTER, CALIFORNIA, 1982.

Parameter*	Equation	R^2
Bulk Yield**	$\hat{Y} = 5437 - 418556\ (O_3)^2$	0.79
Lint**	$\hat{Y} = 1988 - 154532\ (O_3)^2$	0.79
Seed**	$\hat{Y} = 3881 - 256557\ (O_3)^2$	0.81
No. Open Bolls	$\hat{Y} = 349 - 23053\ (O_3)^2$	0.82
Per Boll†	$\hat{Y} = 6.45 - 137.67\ (O_3)^2$	0.67

* Based on total of 4 x 1-m row samples for each chamber; (O_3) = seasonal 7-h mean (ppm).

** Yield in kg/ha.

† In grams.

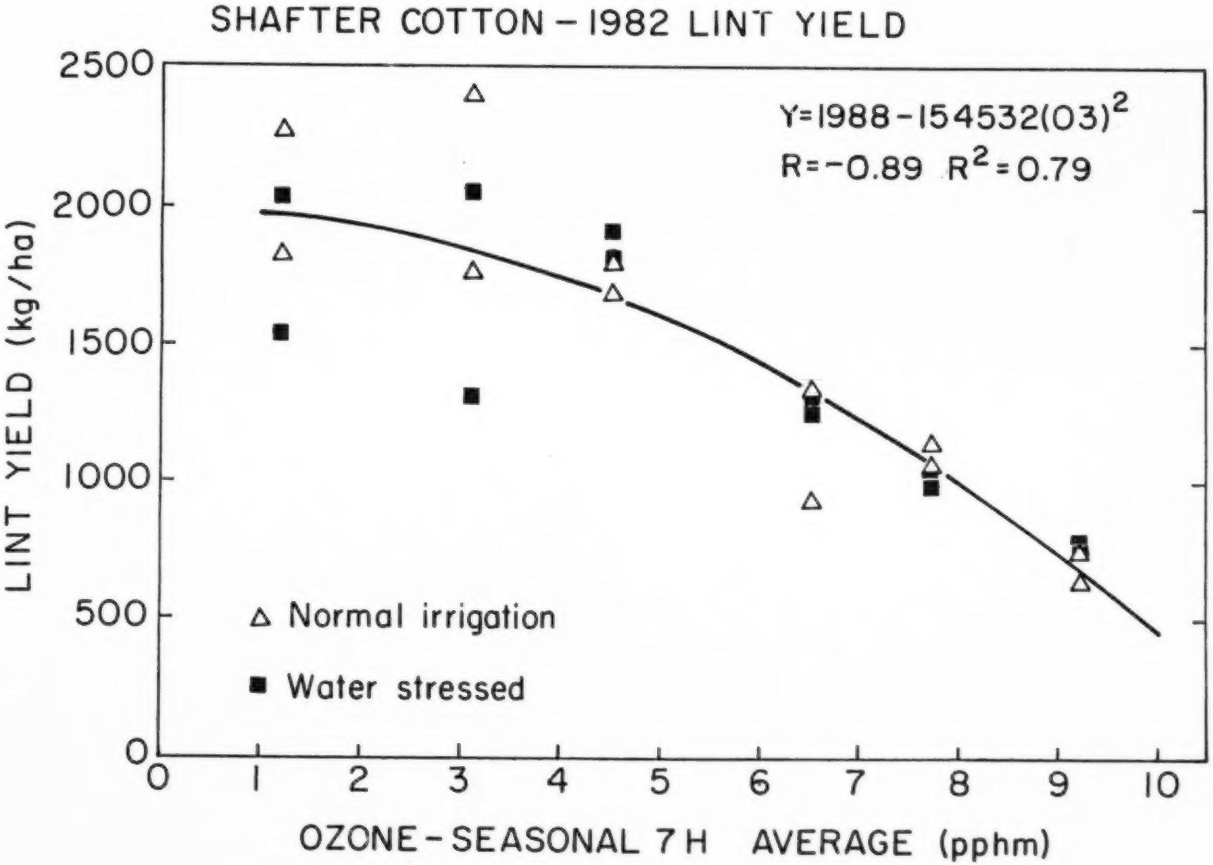


Figure 4.4.3.6. Response of cotton lint yield to O_3 doses in open-top chambers at Shafter, California, in 1982.

TABLE 4.4.3.8. OBSERVED AND PREDICTED O_3-INDUCED PERCENTAGE REFDUCTION IN YIELD PARAMETERS OF SJ-2 COTTON AT SHAFTER, CALIFORNIA, 1982.

Seasonal 7-h O_3 Mean (ppm)	Percent Reduction in Yield (g/m-row)*									
	Bulk Yield		Lint Weight		Seed Weight		No. Open Bolls		Wt. Per Boll	
	Obs.**	Pred.†	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.
0.012	0	0	0	0	0	0	0	0	0	0
0.031	3.3	6.4	1.9	6.5	2.2	6.3	2.7	5.5	0.78	1.7
0.045	6.7	14.6	5.9	14.8	5.6	14.4	6.8	12.7	0	4.0
0.065	36.1	31.8	37.1	32.1	34.4	31.3	29.3	27.2	9.4	8.7
0.077	44.9	45.0	45.1	45.5	43.6	44.4	35.5	38.7	14.3	12.4
0.092	61.7	64.7	61.8	65.4	62.1	63.8	54.7	55.5	15.2	17.9

* Full filtered treatments ($[O_3] = 0.012$) used as base.

** Combined normal and water stressed treatments.

† Best fit prediction equations from linear, quadratic, cubic, and exponential models; see Table 4.4.3.5.

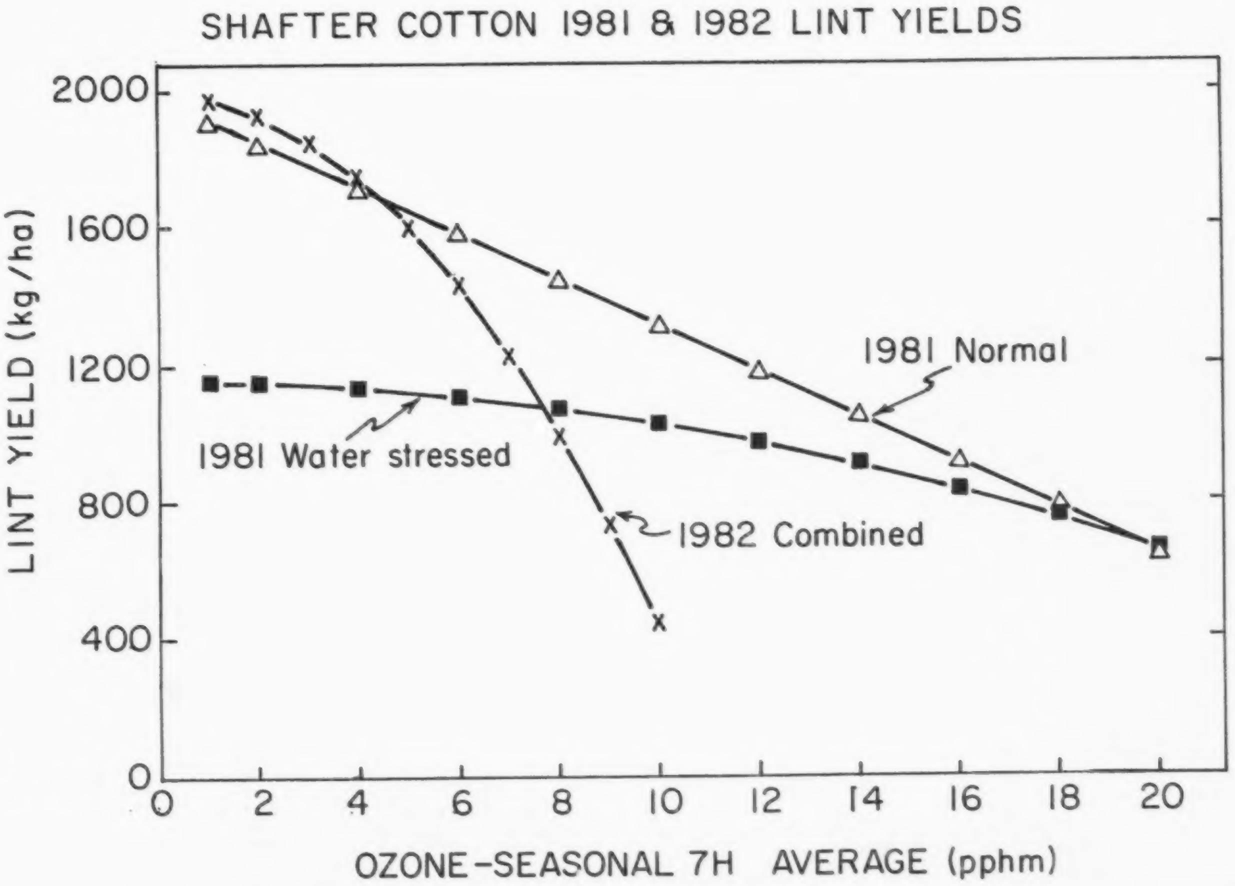


Figure 4.4.3.7. Comparison of 1981 and 1982 cotton yield losses due to O_3 at Shafter, California.

TABLE 4.4.3.9. EFFECTS OF O_3 ON LINT PRODUCTION OF FIELD GROWN* ACALA SJ-2 COTTON IN OPEN-TOP CHAMBERS AT SHAFTER, CALIFORNIA.

	1981			1982		
Treatment**	O_3† (ppm)	Lint Yield‡ (kg/ha)	% Reduction[1]	O_3† (ppm)	Lint Yield (kg/ha)	% Reduction§
CF	0.018	1870	---	0.012	2050	---
Half-F	0.044	1738	7.1	0.031	2085	---
NF	0.072	1490	20.3	0.044	1744	14.9
NF (1)	0.011	1114	40.4	0.065	1139	44.4
NF (2)	0.143	1102	41.1	0.077	1105	46.1
NF (3)	0.183	781	58.2	0.092	701	65.8
Open Plots (AA)	0.077	1649	11.8	0.049	1692	17.5

* Plots received recommended rates of irrigation.

** O_3-added treatments in 1981 2343 (1) NF + 0.03 ppm O_3; (2) NF + 0.06 ppm O_3; (3) NF + 0.10 ppm O_3. In 1982, O_3-added treatments were (1) NF + 1.3 x ambient O_3; (2) NF + 1.7 x ambient O_3; (3) NF + 2.0 x ambient O_3.

† Seasonal 7-h average (0900-1600 PDT).

‡ Average of 2 chambers.

§ Relative to full-filtered chambers.

4.4.3.4 Conclusions

A two-year study at the USDA Cotton Research Center at Shafter, California, on the response of field grown normal and water stressed Acala SJ-2 cotton to O_3 in open-top chambers was completed in 1982. Ambient O_3 concentrations in 1981 reduced lint yields by 20% in normally irrigated plots. Ambient O_3 was much lower in 1982, but lint yields were reduced 15% in NF chambers relative to CF chambers. Doubling the ambient O_3 concentration in chambers reduced lint yield 41% in 1981 and 66% in 1982. Water stressed plants showed little response to O_3 in 1981, but yields in water stressed plots were severely reduced by O_3 in 1982. The greater relative response to O_3 in 1982 was attributed to cooler, more humid conditions during the summer of 1982, which increased the susceptibility of cotton to O_3 injury.

4.5 EFFECTS OF EXPOSURE DYNAMICS: RESPONSE OF SOYBEANS TO AMBIENT O_3 CONCENTRATIONS SUPPLEMENTED WITH CONSTANT OR VARIABLE O_3 CONCENTRATIONS (SERCLAP, Raleigh)*

4.5.1 Introduction

The dose-response experiments in NCLAN were intended to estimate effects at different levels of ambient air quality, but there is a question whether ambient exposures are being adequately simulated when constant O_3 additions are made. A more realistic representation of different air quality levels would be obtained by adding O_3 in different proportions to ambient O_3 concentrations. In this way, the different O_3 treatments would be the ambient O_3 concentration plus different multiples (proportions) of the ambient O_3 concentration.

The primary objective of this experiment was to determine whether O_3 dose-soybean response relationships were affected by the manner in which the O_3 doses were applied.

4.5.2 Materials and Methods

4.5.2.1 Cultural

Soybeans (Glycine max L. Merr. cv. 'Davis') inoculated with Rhizobium were planted with a two-row planter in rows spaced 1-m on 29 June. The soil was Appling (clayey, kaolinitic, thermic, Typic hapludults) previously fertilized according to soil test recommendations. Details of fertilizer and herbicide applications are shown in Table 4.5.1. Plants emerged on 3 July and 10 3-m^2 plots were chosen for each of two blocks based on rate of emergence and uniformity of soil appearance.

Open-top chamber frames were placed over 16 plots on 6 July. Four plots served as nonchambered plots. The plants in each of the two plot rows were thinned to one plant per 2.5 to 7.5 cm on 7 July, resulting in a stand of 18 plants per meter of row in each of the four 1-m sections of row per plot. There was approximately 40 cm of row at both ends of each row where no plant

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* Allen S. Heagle, Virginia M. Lesser, R. B. Philbeck, F. L. Mowry, W. W. Heck, J. O. Rawlings, and Marla J. S. Lee.

TABLE 4.5.1. DATES OF IMPORTANT EVENTS DURING THE 1982 STUDIES AT RALEIGH, NORTH CAROLINA, TO DETERMINE THE RESPONSE OF SOYBEANS TO AMBIENT O_3 CONCENTRATIONS SUPPLEMENTED WITH CONSTANT OR VARIABLE O_3 CONCENTRATIONS.

Month	Day	Event
May	10	Fertilizer applied (0-0-60, N-P-K) 165 lb/acre
June	29	Soybeans planted 'Davis' Lasso applied (2 qt/acre) Lorox planted (1 lb/acre)
July	03	Plants emerged
	06	Plots chosen
	16	Top panels installed
	19	Bottom panels installed, fans on
	20	Begin dispensing O_3
	22	Soil sampled from plots for nutrient analyses
	23	Tensiometers installed
August	11, 31	Foliar injury estimated
September	23	Foliar injury estimated
August	12	Cyhexatin (1.3 g/gal) applied for mite control Permethrin (5.4 ml/gal) applied for armyworm control
	20	Cyhexatin (1.3 g/gal applied)
September	1, 9, 16	Cyhexatin (1.3 g/gal) applied
October	17	Last day of dispensing O_3
November	08	Plants harvested from treatment plots
	11	Soil samples taken from all treatment plots for soil analyses
	22	Plants harvested from companion plots

measures were taken. Soil tensiometers (Irrometer Company, Riverside, California) were installed in each plot at a depth of 30 cm. Tensiometer readings were recorded three times weekly. All plots were irrigated with 2.5 cm of water using drip tubes when 50% of the plots showed tensiometer readings greater than 50%. The weather during this experiment was normal with rainfall during May and early June keeping the field soil too moist to plant. Between planting and crop maturity, 33.2 cm of rain fell and 19.4 cm of irrigation water was applied. Insects and mites were controlled with cyhexatin and permethrin as shown in Table 4.5.1.

4.5.2.2 Pollutant Treatments

Clear polyvinyl chloride-film top panels were installed on 16 July. Bottom panels were installed on 19 July and the fans were turned on. Fans ran daily between 0600 and 2200 EDT. The experimental design employed eight chamber O_3 treatments in each of two randomized blocks. Five O_3 treatments were established using methods for dispensing and monitoring described previously. These five O_3 treatments were charcoal filtered air (CF), nonfiltered air (NF), and air to which 0.02, 0.04, or 0.06 ppm of O_3 (NF + 0.02, NF + 0.04, and NF + 0.06, respectively) was added to ambient O_3 levels for 7 h per day (1000 to 1700 EDT).

The three additional O_3 treatments were NF air to which O_3 was added in set proportions (0.3, 0.6, or 0.9 times) to the amount of O_3 present in the ambient air. The proportional additions were made using an analog controller developed by Gail Bingham and Elizabeth Pierce at Lawrence Livermore National Laboratory. Relationships between ambient O_3, continuously monitored with a Monitor Labs 8410 O_3 monitor which controlled voltage output from the controller to a Griffin GTC-1A ozonizer, and O_3 output as sequentially monitored in the chambers appeared to be linear.

O_3 exposures began on 20 July when first trifoliolate leaves were 75% expanded and continued for 7 hours each day until 17 October when plants in all treatments were physiologically mature (R7 stage). O_3 was not dispensed by either system during periods of rainfall (a total of 24.5 exposure hours during the season) or when either of the systems malfunctioned (a total of 43.5 exposure hours during the season).

4.5.2.3 Response Measurements

Two 'companion' plots outside each chamber plot were used to measure edaphic variability in the field as shown by yield differences for possible covariance analyses. Each companion plot was 2 m of row located 1.2 m east or 1.2 m west of the filter box of each chamber. All cultural practices for plants in the companion plots were the same as for those in the treatment plots.

Plants in the four 1-m rows of the treatment plots were harvested on 8 November. Pods were removed by hand and the number of filled and nonfilled pods per plant were counted. Pods for each 1-m row sample were combined and weighed before threshing. They were threshed as one sample per plot and seed weight per 1 m of row and one 100-seed sample from each 1 m of row (8.1% moisture content) were measured.

4.5.2.4 Statistical Analyses

The analyses of these data took place in several stages. First, the yield data from the companion plots were analyzed to determine the nature of variation within the site. Fitted response surface values for each treatment plot were obtained as well as the average of the two companion plot rows per treatment plot. The fitted values were obtained by regressing the companion plot yield to the field position coordinates of the companion plots in order to determine a polynomial response surface, which was used to predict performance levels for each treatment plot.

Next, an analysis of variance on yield data from the treatment plots was performed. In this analysis, the impact of blocks, treatments, 1 m row positions within treatment plots (position), and position x treatment effects were determined. The key findings of the analyses were that block differences were significant and that, while position effects within chambers were significant, there was no "treatment x position" interaction. Therefore, the third stage of the analysis involved the mean over the four positions of the treatment plot; the analysis consisted of block, O_3 levels, and experimental error. Analyses in this form were used to assess the importance of the covariate yield data obtained from the companion plots. The fitted value for the companion plot response surface seemed to be effective, as measured by the reduction in the experimental error. The averaged value covariate analysis was not effective. The level of significance for the fitted value covariate analysis was marginal and it was decided that the effectiveness of the covariates should be assessed by their impacts on the standard errors of the regression coefficients in the pollution dose-response models.

The next phase of the analysis involved fitting pollutant dose-response models to each of the yield variables measured in the treatment plots. The effectiveness of the covariate data from the companion plots was assessed for seed yield. With minor exceptions, the analyses over replicates failed to show any improvement in the standard errors of the regression coefficients by the use of the covariate data. Consequently, the final dose-response models for yield were fitted without use of the covariates.

The effect of the method of O_3 addition was determined by testing homogeneity of the dose-response curves for the part of the curves affected by the constant and proportional methods of addition. The response curves were not significantly different. Therefore, data for both O_3 addition methods were combined for further analyses. Two classes of models were used to produce dose-response surfaces: polynomial dose-response models and a nonlinear model based on the Weibull probability distribution of sensitivities. The polynomial response models allowed for the degree of polynomial necessary to fit the data.

4.5.3 Results

4.5.3.1 Pollutant doses

The mean seasonal O_3 concentration (mean 7-h/day O_3 concentration during the period of O_3 dispensing) in ambient air (AA), CF, and NF treatments were 0.050, 0.019, and 0.044 ppm, respectively. For the constant addition treatments, the seasonal 7-h/day O_3 concentrations for NF + 0.02, NF + 0.04, and NF + 0.06 treatments were 0.066, 0.086, 0.109 ppm, respectively (Table 4.5.2). For the proportional additions of 0.3, 0.6, and 0.9 times ambient, the seasonal 7-h means were 0.065, 0.081, and 0.092 ppm, respectively. The daily 7- and 24-h mean O_3 concentrations in AA from 10 July through 17 October are shown in Figure 4.5.1. The mean seasonal diurnal fluctuations in O_3 concentrations for AA and for the chamber treatments are shown in Figure 4.5.2.

4.5.3.1 Yield

The analyses of variance showed significant effects of block, O_3, and the row position within plots, but there were no position by treatment interactions. As the O_3 dose increased, there was a decrease in all yield measures (Table 4.5.3). The polynomial analyses for seed weight per meter of row (yield) showed significant linear, quadratic, and cubic relationships between the O_3 dose (types of addition combined) and yield (Table 4.5.4). The Weibull analyses showed a significant linear relationshp between the O_3 dose and yield (Table 4.5.4). O_3 dose-response relationships for seed yield for the polynomial and Weibull models (types of additions combined are shown in Figure 4.5.3.

4.6 QUALITY ASSURANCE FOR 1982*

4.6.1 Air Monitoring

A systems evaluation of QA procedures for instrumentation monitoring and dispensing of air pollutants was made August 16-24 for the six NCLAN sites by Grady Neely, NCLAN Quality Assurance Officer (QAO). He indicated in his report, "No significant performance problems were identified at any of the research locations. All sites were following Instrument QA procedures very closely and seemed to have highly motivated personnel conducting the research."

The final report of the 1982 annual performance audits on the air monitoring analyzers at each of the NCLAN sites is on file with the QAO in Corvallis. J. L. McKee and R. W. Murdock of the Research Triangle Institute, Research Triangle Park, North Carolina, conducted the audits in September and prepared the report.

The accuracy of the analyzers at all research locations in 1980, 1981, and 1982, as determined by audits, is shown in Table 4.6.1. A result of excellent, satisfactory, or unsatisfactory indicates the response of the analyzer was within 5%, 5-15%, or greater than 15%, respectively, of the known amount of standard gas presented to the analyzer. Summary results for 1982 reveal for the twenty-eight O_3 analyzers audited, eighteen were excellent and ten were satisfactory. Of the fifteen SO_2 instruments, seven were excellent, seven were satisfactory, and one was inoperative. The results of the audit of the three total oxides of nitrogen monitors show that the nitric oxide channel of one of the O_3 analyzers was excellent. One did not record nitric oxide and one was inoperative. The total oxides of nitrogen channel results are the

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* James Miller and Grady Neely, Corvallis Environmental Research Laboratory, Corvallis, Oregon.

TABLE 4.5.2. O_3 CONCENTRATIONS* FOR STUDIES AT RALEIGH, NORTH CAROLINA, TO DETERMINE THE RESPONSE OF SOYBEANS TO CONSTANT OR VARIABLE O_3 ADDITIONS TO AMBIENT O_3 CONCENTRATIONS.

Treatment	7-h/day Values			1-h/day Peak Values		
	Seasonal Mean	Highest	Second Highest	Seasonal Mean	Highest	Second Highest
No Addition						
AA	0.050	0.091	0.083	0.062	0.114	0.102
CF	0.019	0.035	0.033	0.028	0.054	0.051
NF	0.044	0.081	0.069	0.056	0.106	0.091
Constant Addition						
NF + 0.02	0.066	0.104	0.098	0.080	0.131	0.119
NF + 0.04	0.086	0.124	0.123	0.106	0.149	0.148
NF + 0.06	0.109	0.168	0.147	0.134	0.211	0.186
Proportional Addition						
NF (1.3)	0.065	0.119	0.113	0.088	0.149	0.139
NF (1.6)	0.081	0.154	0.143	0.111	0.186	0.177
NF (1.9)	0.092	0.200	0.164	0.126	0.225	0.216

* Values for the period 20 July to 17 October 1982.

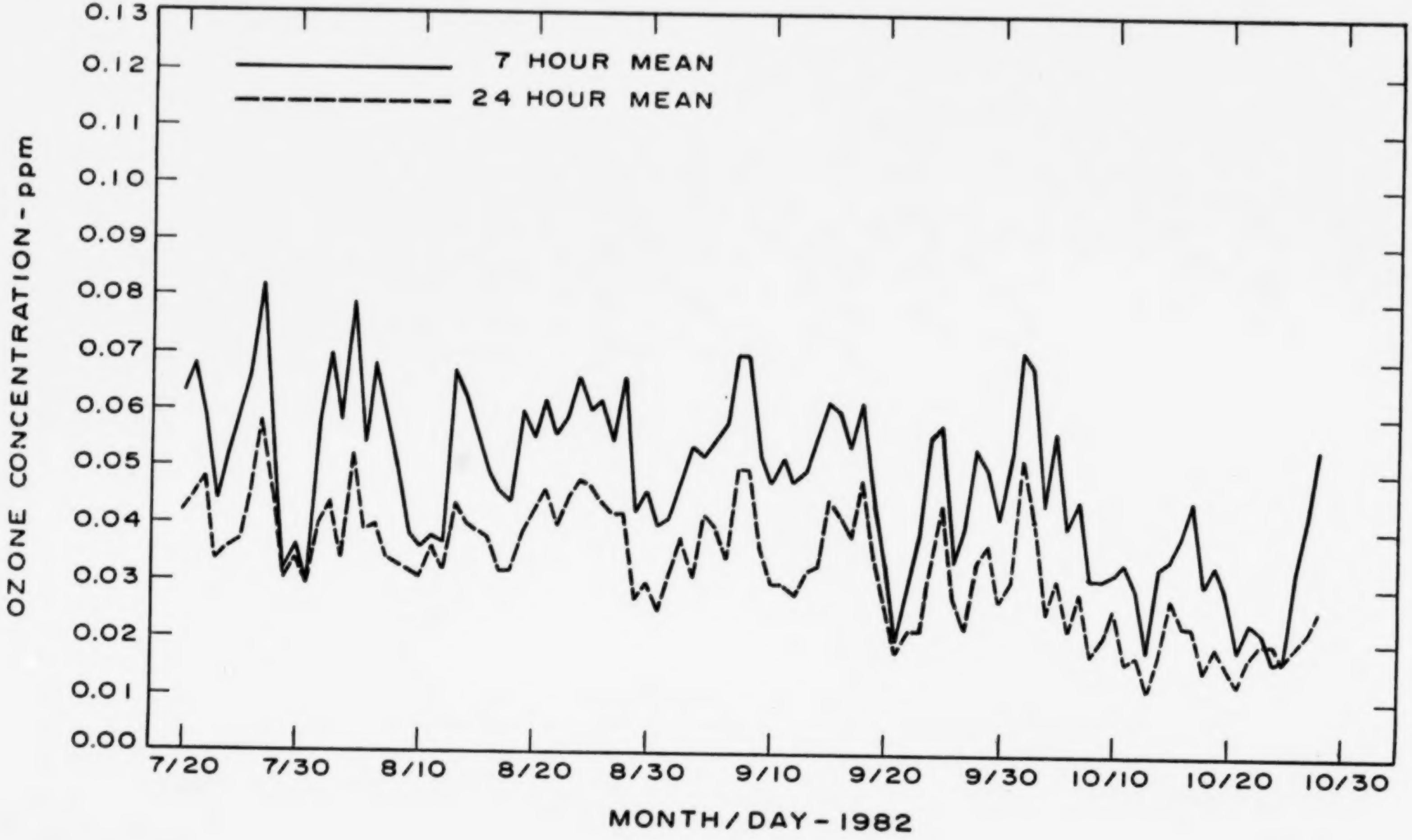

Figure 4.5.1. Daily 7-h (1000 to 1700 EDT) and 24-hr mean O_3 concentrations during the period of exposures for the 1982 soybean experiment at Raleigh, North Carolina.

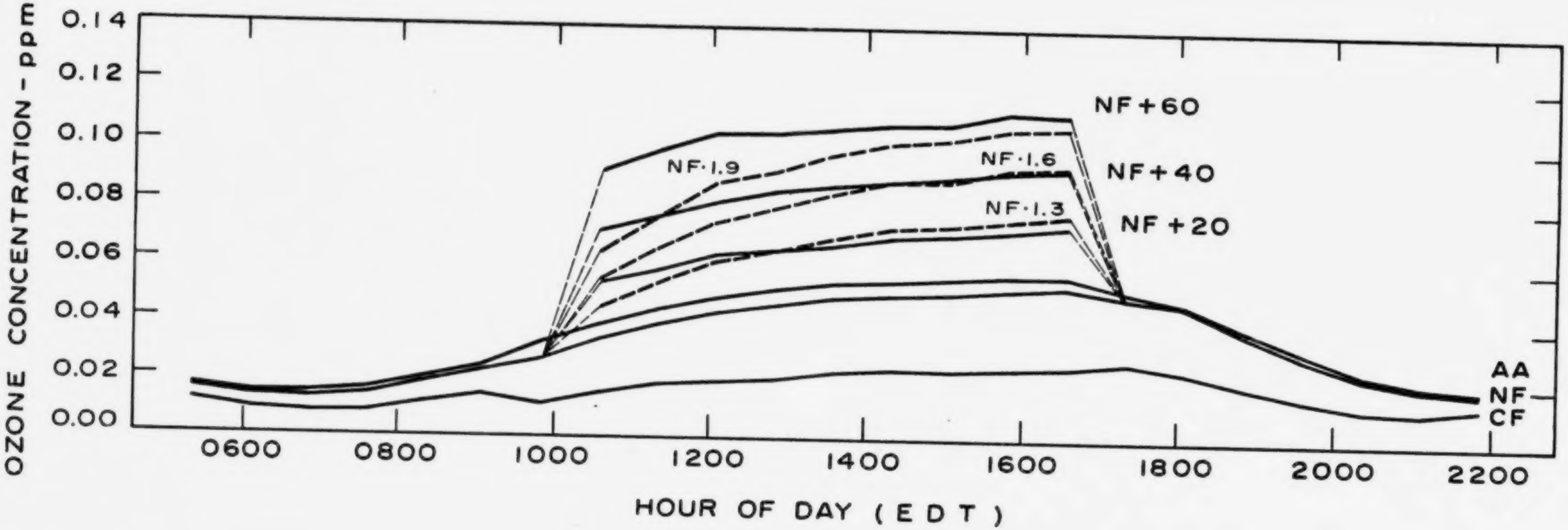

Figure 4.5.2. Seasonal (20 July to 17 October) diurnal fluctuation in concentration for the variable and constant O_3-addition treatments for ambient air, nonfiltered-air chambers, and charcoal filtered-air chambers in the 1982 soybean experiment at Raleigh, North Carolina.

TABLE 4.5.3. WEIGHT OF FILLED PODS AND SEED WEIGHT PER METER OF ROW AND 100-SEED WEIGHT FOR 'DAVIS' SOYBEANS EXPOSED TO DIFFERENT DOSES OF O_3 ADDED IN CONSTANT OR VARIABLE AMOUNTS TO O_3 IN AMBIENT AIR AT RALEIGH, NORTH CAROLINA.**

Type of O_3 Addition	Seasonal 7-h/day Mean O_3 Conc.	Filled Pod Weight per Meter*	Seed Weight per Meter*	100-Seed Weight*
None	ppm	g	g	g
CF	0.019	622	468	16.9
NF	0.044	637	478	16.2
Constant				
NF + 20	0.066	475	354	14.6
NF + 40	0.086	435	319	13.4
NF + 60	0.109	323	240	13.2
Variable				
NF (1.3)	0.065	537	399	14.3
NF (1.6)	0.081	434	324	14.0
NF (1.9)	0.092	347	259	13.5

* Each value is the mean of 16 samples (from 1 m of row each).

** Ambient air plots were placed at the ends of rows in both blocks due to inadequate space for proper randomization. For the four AA plots, the mean weight of filled pods, seeds, and 100-seed weights per meter were 449 g (range 413 to 486 g), 330 g (range 306 to 360 g), and 14.8 g (range 14.6 to 15.0 g), respectively.

TABLE 4.5.4. POLYNOMIAL AND WEIBULL EQUATIONS FOR YIELDS OF 'DAVIS' SOYBEANS EXPOSED TO CHRONIC DOSES OF O_3 IN OPEN-TOP FIELD CHAMBERS AT RALEIGH, NORTH CAROLINA.

Polynomial*	$Y = 356.6 + 9513.8\ x - 200059.8\ x^2 + 945528.5\ x^3$
Weibull*	$Y = 491.8 \exp [(-x/0.121)^{2.26}]$

* Y = seed yield (g) per meter of row.

x = O_3 dose (ppm) - seasonal 7-h/day mean.

Standard errors for polynomial terms were: $b_1 = \pm 3570$; $b_2 = \pm 61667$; $b_3 = \pm 315880$. Standard errors for Weibull terms were $b_1 = \pm 18.96$; $b_2 = \pm 0.0051$; $C = \pm 0.3823$.

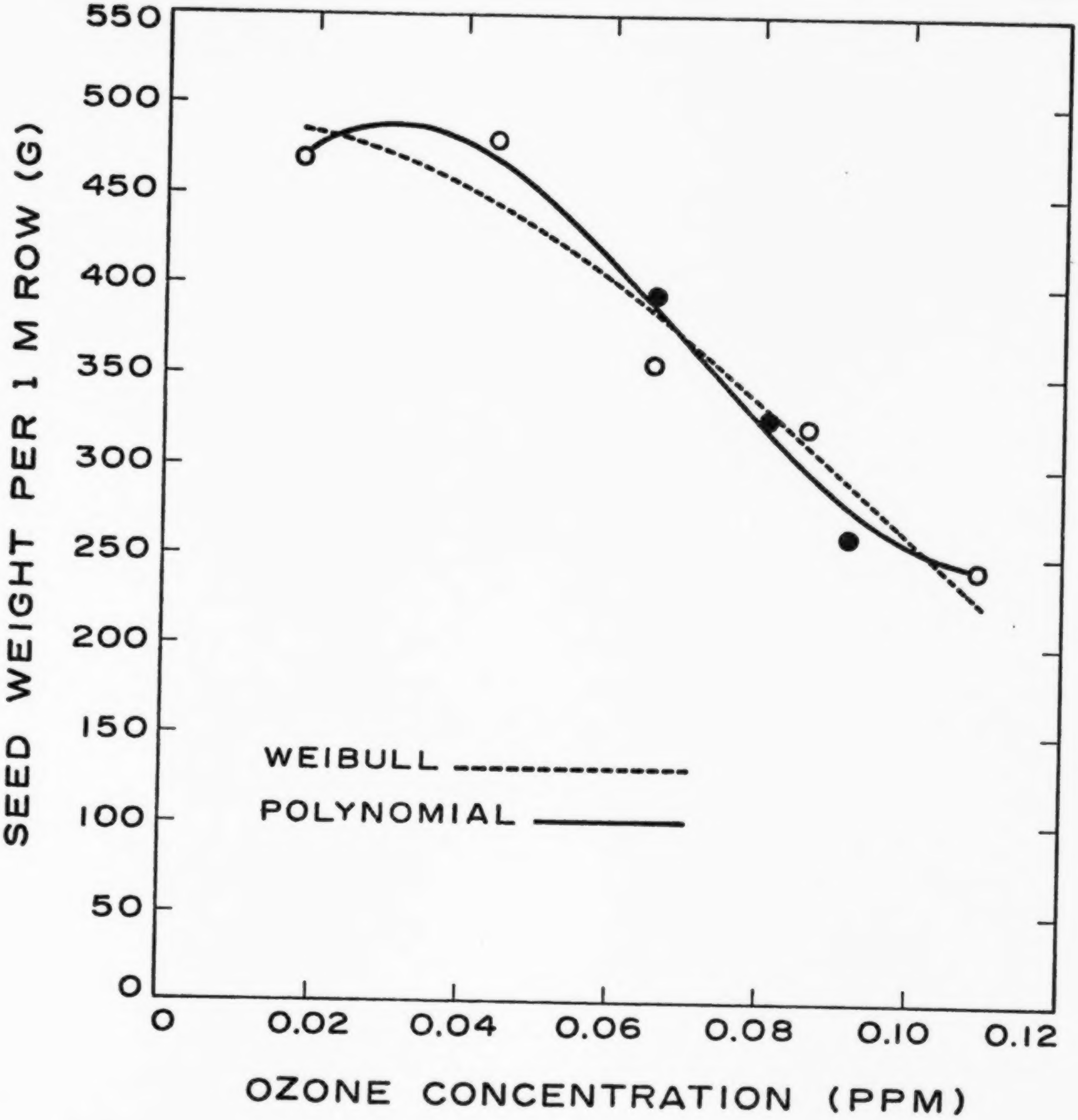

Figure 4.5.3. Relationships between seasonal 7-h per day O_3 doses and seed yield as predicted by polynomial and Weibull analyses for the 1982 soybean experiment at Raleigh, North Carolina. o = treatment mean measured values for CF, NF, and constant addition treatments. • = treatment mean measured values for proportional additional treatments.

TABLE 4.6.1. SUMMARY OF NCLAN ANALYZER AUDITS FROM 1980 TO 1982.

Audit Site and Date	O_3			SO_2			NO_x			CO_2			Total
	E	S	U/I	E	S	U/I	E	S	U/I	E	S	U/I	
Raleigh													
Sept. 1980					1	1							2
July 1981		4		2	2				1				9
Sept. 1981	4			3	1				1				9
Sept. 1982	3	2		2			1						8
Beltsville													
July 1980			1		1								2
July 1981		1	1		2					1			5
Sept. 1981	2	1		1	1								5
Aug. 1982	3	2			1	1							7
Ithaca													
Sept. 1980	1	2	1	1	1								6
July 1981	4			2	2					1			9
Sept. 1981	5			1	3							1	9
Sept. 1982	4	1		2	2								9
Riverside													
Sept. 1980	1	4											5
July 1981	2	1	1										4
Argonne													
July 1981	2	3		2	3			1					11
Sept. 1981	3	1	1	2		3		1	1				12
Sept. 1982	1	2		1	1				1				6
Shafter													
Sept. 1981	3		1										4
Aug. 1982	2	2											4
Livermore													
Sept. 1981	5			4						1			10
Sept. 1982	4			2	2					1			9
Corvallis													
July 1980	2				1			1					4
July 1981	2			1				1					4
Sept. 1981	2			1			1						4
Sept. 1982	1	1			1		1						4
Totals													
Sept. 1980	4	6	4	1	4	1		1					21
July 1981	10	9	2	7	9			2	1	2			42
Sept. 1981	22	4	2	11	6	3	1	1	2	1		1	54
Sept. 1982	18	10		7	7	1	2		1	1			47

E = Excellent; S = Satisfactory; U = Unsatisfactory; I = Inoperative.

same as the nitric oxide channel. Of the monitors operating, the NO_2 channel in each one was excellent. The results of the one CO_2 analyzer audited was excellent.

The precision of the individual analyzers at each location in 1982, as determined from the submitted zero and span gas data, is presented in Table 4.6.2. The 95% probability limits were determined as written in the Federal Register, Thursday, May 10, 1979.

4.6.2 Biological

This report summarizes the second year of results for NCLAN's Biological Quality Assurance Plan, BQAP. A systems evaluation of planned QA procedures trip was made to each research location August 16-24 by Grady Neely, NCLAN Quality Assurance Officer (QAO). Each station had made plans to follow QA procedures for weighing during the harvest or fall season. Soil moisture procedures were being followed; however, all researchers were not recording the results of their efforts. This will be corrected during the 1983 growing season.

A BQAP questionnaire was mailed by the QAO to the Biological Quality Assurance Leader (BQAL) for each site in January 1983 to determine how closely QA procedures were followed in 1982. The results indicate (1) most weighing QA procedures were adhered to at each location, (2) most QA procedures were followed at each site for soil moisture measurements, and (3) data handling procedures were being adhered to at all stations. All questionraires will be maintained by the QAO.

A summary of checks for weight measurement accuracy, presented in Table 4.6.3, indicates all reporting station weights were within 1% of their true weights at least 90% of the time. Three locations were always within 1% of the true weight.

All stations are now aware of and in compliance with QA documentation requirements. The NCLAN QAO will work with the researchers in 1983 in making additions and updating the BQAP.

5.0 ASSESSMENT OF CROP LOSS AND THE ECONOMIC CONSEQUENCE OF THE BIOLOGICAL RESPONSE OF CROPS TO O_3

5.1 AIR QUALITY DATA INTERPRETATION*

5.1.1 Introduction

Estimates of the exposure levels which crops experience in different parts of the country are needed to complete an economic assessment of potential O_3 related losses to agriculture. The work presented in the following section uses the available surface monitoring data to develop estimates of chronic O_3 exposure in the continental United States for 1978-1982. A

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* James Reagan, U.S. Environmental Protection Agency, Environmental Sciences Research Laboratory, Research Triangle Park, North Carolina.

TABLE 4.6.2. SUMMARY OF NCLAN ANALYZER PRECISION IN 1982.

Site	Analyzer	Serial Number	Dates	PTS	95% Probability Limits Upper	Lower
Raleigh	ML 8450/SO_2	122	8/27 - 9/24	6	10.8	-10.6
	ML 8450/SO_2	478	6/28 - 8/25	9	12.9	-10.2
	ML 9450/SO_2	480	6/28 - 9/24	17	23.5	-18.2
	ML 8410/O_3	284	7/20 - 8/26	9	13.7	-20.0
	ML 8410/O_3	121	7/20 - 8/26	9	10.7	-16.0
	ML 8410/O_3	188	6/28 - 8/23	8	24.1	-20.6
	Bendix/O_3	6753	6/28 - 9/28	14	14.6	-16.7
	Bendix/O_3	83979	9/02 - 9/27	6	18	-19.9
	Bendix/O_3	71584	7/20 - 8/26	8	6.3	-15.8
	Bendix/NO_x	62615	8/30 - 9/02	3	24.8	-41.8
Beltsville	Bendix/O_3	34137	7/06 - 10/7	10	1.1	-2.2
	Bendix/O_3	296782	7/08 - 10/7	8	5.1	-3.1
	TECO/O_3	139	8/16 - 9/30	6	1.4	-2.1
	ML 8410/O_3	179	8/18 - 8/30	3	1.2	-0.2
Ithaca	ML 8410/O_3	167	8/20 - 10/1	11	12.2	-2.2
	ML 8410/O_3	300	7/29 - 9/10	9	4.3	-7.6
	ML 8410/O_3	169	5/10 - 7/14	44	15.7	-19.2
	ML 8410/O_3	331	5/25 - 10/1	68	9.1	-10.0
	ML 8410/O_3	283	5/10 - 10/1	71	12.8	-12.7
Argonne	Bendix/O_3	300452	6/01 - 8/29	40	3.8	-4.2
	Bendix/O_3	32977	6/01 - 8/29	39	3.4	-5.2
	Bendix/O_3	7503	6/01 - 8/29	31	2.7	-3.9
Shafter	Dasibi/O_3	1132	2/18 - 4/01	18	1.7	-3.6
	Dasibi/O_3	1183	2/18 - 4/01	18	0.9	-4.0
	Dasibi/O_3	1140	2/18 - 4/01	18	3.5	-0.7
	Dasibi/O_3	1183	6/01 - 7/16	18	3.8	-3.7
	Dasibi/O_3	1140	6/01 - 7/16	18	2.2	-1.1

TABLE 4.6.3. SUMMARY OF CHECKS FOR WEIGHT MEASUREMENTS.

	Location	Total # Days Checked	Weights Checked	Mean % Accuracy	Range % Accuracy	% Within 1.0%
1.	Argonne	6	69	0.059	-1.70 - 0.5	98.6
2.	Beltsville	6	73	0.088	0.00 - 0.6	100.0
3.	BTI	10	152	0.007	-0.06 - 0.13	100.0
4.	Tracy	12	312	0.438	-10.0 - 14.0	91.3
5.	Raleigh	13	302	0.035	-0.03 - 1.0	100.0
6.	Shafter*					

* Weights (100, 200, and 500 g) were certified by the State of California Department of Weights and Measures (Riverside County) to be within 7 grains (0.454 g) of nominal value. Startup, mid-day, and end of day balance checks were within 1% of true weight. The results were not recorded, however.

comparison of the standard NCLAN chamber exposure averaging to other exposure measures (averages, maxima) was made to explore the nature and strength of the relations between different methods of expressing the exposure.

The principal caveat on this work is the connection between urban and rural O_3 levels, while data quality and availablility are secondary caveats. Different observers may feel that the resultant exposure estimates are either understated or overstated. This work was carefully prepared to avoid any known bias in either direction.

5.1.2 Methodology

5.1.2.1 SAROAD Data

Air quality monitoring data from State and Local Air Monitoring Stations (SLAMS) are archived in EPA's Storage And Retrieval Of Aerometric Data (SAROAD) base. All of the available data from 1978-1982 were retrieved. Most of the fourth quarter data from 1982 were unavailable when this work was done, preventing estimation of a seasonal average including October. Although data are to be submitted to SAROAD quarterly, some data comes annually, thus possibly accounting for some of the other missing 1982 sites. Table 5.1.1 shows the number of sites reporting data for each year and the number having sufficient data to form a May-September average based on completeness criteria discussed in 5.1.2.3.

Monitoring guidelines published by EPA on May 10, 1979, implemented a number of quality assurance procedures to be used at SLAMS. A change in the calibration procedure resulted in a reduction in measured O_3 levels of 10 ± 5 ppb. There was also a reduction in the variability between different sections of the country. The older method had a systematic bias upward, but a much higher variance on repetitions. No comprehensive list of changeover dates has been compiled; however, California changed in 1975 and Illinois switched on January 1, 1979.

Oxidant data like most air quality data is fairly expensive to collect. Monitors cost from $4,000 to $6,000. There is the added expense of maintenance, quality control, quality assurance, and data capture/reduction/editing/archival. SAROAD is the most complete archive of these data available, but the principal reason for monitoring is to check compliance against the O_3 standard. The SLAMS are generally not situated for crop exposure monitoring. Later discussion shows the application of SLAMS data to the rural estimates.

A file format consisting of the SAROAD site identification, parameter code, monitoring method, year, and data for the whole year was established. This design permits inclusion of a data set for any parameter which consists of hourly observations. It also facilitates multiple month scans for average generation or other statistical manipulation. There were some 1.5 million SAROAD card images per year to process into the O_3 data file. A list of the sites for which data were reported was used to retrieve the site location and characteristics from the SAROAD site file.

TABLE 5.1.1 QUALIFYING SITES IN DIFFERENT YEARS.

Year	Total Sites	Qualified Sites	% Qualified
1978	574	247	43
1979	652	334	51
1980	752	363	48
1981	740	478	65
1982	652	404	62

5.1.2.2 Station Selection

The proper selection of stations is one of the most important tasks. Only a few stations are in truly rural settings, with the vast majority in urban clusters. Bridging the urban to rural gap with the available data is the weakest link in this assessment. There are, however, a number of considerations which permit the assessment to be achieved.

The largest O_3 gradients occur at the urban scale. The averaging effect over long periods tends to remove the effects of discontinuities such as power plant or urban plumes which exist on a day to day basis. A more serious problem in urban settings is the reduction of O_3 by nitric oxide and concurrent underestimation of the O_3 present. In some cities, the density of stations is in excess of assessment needs and could be reduced. Consequently, the core area of several cities was excluded. The perimeter stations for the very large urban areas provide sufficient information for rural estimates without repetition from the additional city stations. Los Angeles is a special case because the values are unlike anywhere else in the country. It is a separate meteorological regime, as evidenced by the oxidant levels, and requires techniques not necessary for this assessment. Consequently, the Los Angeles area has been excluded from the analysis. Table 5.1.2 shows the areas in which station data were excluded.

The SAROAD site file includes a classification of the general area around the monitoring site: center city, suburban, rural, or remote. There are few remote sites and the rural classification does not seem to be entirely accurate for all sites, preventing usage based on classification alone. A Center City designation occurs for towns of many sizes. It is a useful criteria, however, for determining stations potentially subject to direct automotive emissions. No sites designated Center City in the 14 areas listed in Table 5.1.3 were used in the assessment.

5.1.2.3 Exposure Statistics

In making a national assessment, the NCLAN loss functions must be coupled with a comparable exposure statistic. Less potential error is introduced in the assessment if the exposure statistics used are the same as the plant exeriments. Any other exposure statistic requires development of a relation between experimental measures and the alternate statistic. Use of another statistic diminishes the quality of the assessment, since other questions are added about the strength of the measure, its relation to actual crop damage, etc. Therefore, the exposure statistic used for this assessment is the average level of O_3 from 0900-1600 LST (local standard time) for the periods of crop growth.

The use of a fixed period average lends itself to an elegant way to handle the missing data. A minimum data set was required based on the following algorithm for an N month growing season: (1) at least N - 1 months must have 16 or more days with all seven hours present; and (2) there must be at least 16 * N days of complete data. The first requirement usually, but not always, guarantees the second. Data were stratified by hour and the average

TABLE 5.1.2. AREAS IN WHICH STATION DATA WERE EXCLUDED.

City	Latitude		Longitude	
	Min	Max	Min	Max
Los Angeles, CA	N33.5	N34.5	117.0W	119.5W
San Francisco, CA	36.5	38.5	122.0	123.5
St. Louis, MO	38.6	38.8	90.17	90.27
Chicago, IL	41.5	42.0	87.35	87.85
Philadelphia, PA	39.9	40.1	75.1	75.2

TABLE 5.1.3. CITY CENTER DATA EXCLUDED.

City	Latitude		Longitude	
	Min	Max	Min	Max
Phoenix, AZ	N33.0	N34.0	111.5W	112.5W
Denver, CO	39.5	40.0	104.5	105.5
Albuquerque, NM	35.0	35.5	106.0	107.0
Dallas-Ft. Worth, TEX	32.5	33.0	96.5	97.5
St. Louis, MO	38.5	39.0	90.0	90.5
Chicago, IL	41.5	42.0	87.0	88.0
Chicago, IL	42.5	43.5	87.5	88.0
Charlotte, NC	34.5	35.5	80.5	81.5
Cincinnati, OH	38.5	39.5	84.0	85.0
Washington, DC	38.5	39.5	76.5	77.5
Philadelphia, PA	39.5	40.5	74.5	75.5
New York, NY	40.5	41.0	73.5	74.5
Tampa, FL	27.0	38.5	82.0	83.0
Boston, MA	42.0	42.5	70.5	71.5

of the available data in each hour was taken to yield the seasonal mean. It was in effect the mean of the seven hour average profile. No data from a station which met the minimum data criteria were excluded.

5.1.2.4 Kriging

Air quality estimates are to be paired with county level crop production figures to estimate yield change from crop dose-response curves. The following discussion outlines the technique used to translate the SAROAD monitoring data into national exposure assessments.

In performing the assessment, a statistical technique called "Kriging" was employed to estimate gridded values from irregularly spaced, generally clustered monitoring data. Kriging was first developed for the mining industry to estimate where the best grade ore was located from samples taken intermittently in the field. There are two main advantages in Kriging over conventional interpolation techniques such as $1/R^2$. The distance between monitored points is taken into account as well as the distance to the estimation point. A second advantage is kriging's smoothing properties. The O_3 data used was primarily designed to monitor worst case air pollution events. A smoothed estimate provides a much better approximation of exposure than other estimates might provide.

There are several classical methods for producing spatial interpolations such as polynomial curve fitting, weighted averages by $1/R$ or $1/R^2$, and arithmetic averaging of local points. A problem with these methods occurs when the data are clustered (as the urban monitoring clusters in major SMSA's). In large area domains clusters have too much weight although the representative area is a small part of the domain. For example, if three clustered monitoring locations really represent one point and one location is isolated from the other three, a point estimated under arithmetic, $1/R$, or $1/R^2$ would have contributions of about 1/4 from each monitoring location. Since Kriging looks at the interstation distance, the Kriging weights might give the cluster a weighting of 60 percent and the remainder to the isolated location. Simpler averaging methods do not look at interstation distances, only estimate to point distances.

In Kriging the recorded measurements are treated as regionalized variables. Many natural phenomena can be considered regionalized variables which are realizations of points spread out in space/time which reflect the underlying structure of the field from which they came plus random error. When properly used the Kriging methodology provides an estimation error for the interpolated values. In other applications the error fields plotted geographically may be used to position additional sampling locations according to a strategy of maximizing uncertainty reduction.

The expectation of a regionalized variable is a constant:

$$E\,[z(x)] = m(x) = m. \tag{1}$$

Differences between sampling results at different locations are not based on actual locations, but instead are based only on the vector between the locations. Therefore, the covariance can be expressed as:

$$E\,[(z(x)-m)^2] = \mathrm{Var}\,[z(x)] = k(o). \quad (2)$$

The basic assumptions can then be expressed as:

$$E\,[z(x+h) - z(x)] = 0 \quad (3)$$

$$\mathrm{Var}\,[z(x+h) - z(x)] = 2\,\gamma\,(h) \quad (4)$$

5.1.2.5 Variograms

From Equation (4) above the variance-distance relation called the semi-variogram is derived as:

$$\gamma(h) = \tfrac{1}{2}\,\mathrm{Var}\,[z(x+h) - z(x)] \quad (5)$$

$$= \tfrac{1}{2}\,E\,[(z(x+h) - z(x))^2] \quad (6)$$

$$= \tfrac{1}{2} \sum_h (z(x+h) - z(x))^2 / N_h \quad (7)$$

The variogram in Equation (7), as it usually is known, is the mean squared difference between all pairs of points separated by distance, h. A simple plot of the variogram is shown in Figure 5.1.1. A nugget is the inherent variance at zero distance. For this study an estimate of replicate variance based on the SLAMS operating guidelines allowance of a nominal 15% span drift was used to obtain:

$$\gamma(0) = \tfrac{1}{2} \sum_{i=1}^{N} (0.15)^2\,(z_i)^2/N \quad (8)$$

There was a discontinuity from this value to the zero intercept of the straight line approximation made to the initial portion of the semi-variogram. The latter portion of the semi-variogram was generally estimated by the "sill," a horizontal line representing the maximum variance between stations that is achieved in spite of increasing distance between stations. These variogram equations are given in Table 5.1.4.

An arbitrary cutoff of 500 kilometers was established beyond which the data from a station would not be used for an estimation. Several of the variograms show some instability at 500-700 kilometers, beyond which a sill value would be used. There are some anecdotal observations that using visibility as a surrogate might allow assumptions of continuity up to 300 kilometers. A desire to provide estimates for as much of the country is balanced by a limitation on the credible distance the data from sites can be extrapolated. The five nearest stations, within 500 km, were used to provide estimates. If five stations were not available, then no estimate was made unless a nearest neighbor within 30 km was available, in which case the average for that station was used as the estimate. This limitation largely arose in areas where O_3 is not *a priori* considered to be a problem at all, such as the northern tier of states in the prairie and mountains of the West.

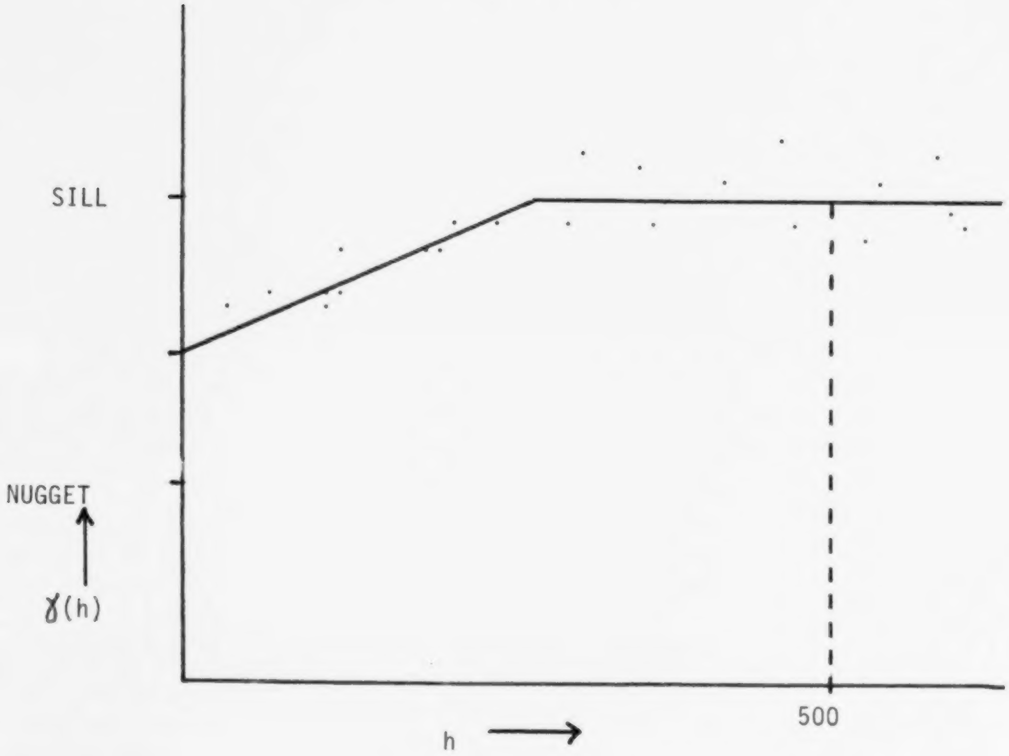


Figure 5.1.1. Plot of a hypothetical variogram.

TABLE 5.1.4. SEMI-VARIOGRAM EQUATIONS.

			Straight Line			
Season	Year	Zero Distance Ordinate	Intercept	Slope	Maximum Distance	Sill
APR-MAY	1978	27.0	34.1	1.380	49.0	101.5
	1979	18.7	55.9	0.075	500.0	---
	1980	20.9	54.7	0.100	500.0	---
	1981	19.1	32.1	0.046	500.0	---
	1982	22.5	26.0	0.362	72.5	52.3
APR-JUN	1978	23.3*	18.7	1.710	55.6	114.0
	1979	21.8	41.7	0.293	152.0	86.0
	1980	22.9	61.1	0.078	500.0	---
	1981	20.3	39.5	0.033	500.0	---
	1982	22.3	31.4	0.252	81.0	51.8
MAY-SEP	1978	25.1	68.6	0.084	500.0	---
	1979	22.9	37.7	0.417	117.0	86.5
	1980	25.6	43.9	0.498	98.2	92.8
	1981	22.6	36.6	0.182	156.4	65.1
	1982	22.0	27.2	0.362	106.4	65.7
JUN-SEP	1978	25.4	72.0	0.112	500.0	---
	1979	23.0	42.8	0.393	130.2	94.0
	1980	26.3	49.2	0.489	125.0	110.3
	1981	23.1	32.5	0.288	137.1	72.0
	1982	21.4	32.4	0.408	109.0	76.0
JUN-OCT	1978	21.8	73.8	0.063	500.0	---
	1979	20.2	28.9	0.617	93.0	86.2
	1980	22.8	48.7	0.271	138.4	86.2
	1981	20.0	21.8	0.323	126.4	62.7

* Intercept used rather than ordinate.

Verification of a variogram is achieved by taking the location information for each station in turn and treating that as a point to be estimated by the Kriging program, but ignoring the data from that station in generating the prediction. This provides a predicted value at a site with a known concentration. The distribution of:

$$\frac{\text{Predicted - Observed}}{\text{Kriging Error}}$$

should be normally distributed with zero mean and unit variance. For this exercise the residuals were always symmetrical with zero mean and usually some deviation from unit variance. Quite often a histogram of the residuals has a higher peak at zero than the N(0,1) curve.

In performing kriging estimates, there was a desire to have some continuity to the air mass which was being estimated. For this reason, the continental United States was divided into six regions. The Continental Divide is the major boundary, and that portion east of it contains the majority of land area and monitoring stations. South Florida and south Texas below latitude N27° were not included because these areas are in an equatorial, maritime meteorological regime during the oxidant months and are, therefore, not a part of the eastern continental air mass. The Pacific Northwest Coast of Washington, Oregon, and northern California was partitioned from the western U.S. due to the climatological influence of the Japanese Current and Pacific Cascade mountain range. The central California area was partitioned at the Sierra Nevada mountain range with Los Angeles separately isolated and ignored for previously stated considerations. Only monitoring station data in each region were used in estimating points in that region, resulting in a significant portion of the northern Great Basin region having no estimates.

5.1.2.6 Application of Kriging

Once a variogram has been produced, the stations selected and location of the estimate established, the following system of equations is solved to obtain the weighting factors.

$$\sum_{j=1}^{n} \lambda_j \, \gamma(|x_i - x_j|) + \mu = \gamma(|x_i - x_0|), \quad i = 1, \ldots, n \qquad (9)$$

$$\sum_{i=1}^{n} \lambda_i = 1, \text{ where:} \qquad (10)$$

n = number of station values used

$z(x_i)$ = realization of the regionalized variable at location, x_i

x_0 = location to be estimated

$\gamma(x_i - x_j)$ = value of the gamma (variogram) function at the Euclidian distance between x_i and x_j (if $i = j$, $x_i - x_j = 0$)

λ_j = weighting factor at location j.

Then from the solution for the λ_i the estimation at point, x_0, is:

$$z(x_0) = \sum_{i=1}^{n} \lambda_i \, z(x_i) \tag{11}$$

Although county level estimates are desired, a grid of squares ½° Latitude x ½° Longitude was estimated using the qualified SAROAD data. County values can be interpolated from the gridded values for assessment calculations.

5.1.3 Results

5.1.3.1 Exposure Statistic Comparison

Comparison of the seven hour (0900-1600) average for a season to other seasonal exposure statistics provides a bridge from one to the other. Table 5.1.5 is a comparison of four exposure statistics for 24 combinations of months during 1978-1982. These data are based on the calculation of the four exposure statistics at each site meeting the minimum data requirements (4 hrs valid data/day) and station selection criteria outlined previously for the seven hour average. Each average shown is the average across all monitoring stations for that exposure statistic with the standard deviation for the station seven hour mean also given. As noted before, the change in calibration procedures after 1978 makes that year different from the succeeding years, which can be compared with one another. Some of the 1982 data do not appear to have been available in early 1983 when these assessments were started. That is the reason no attempt was made to perform a June-October 1982 assessment.

There is a very strong relationship between the seven hour mean and the daily peak average. A weak relationship exists between the seven hour mean and the highest peak in the season, but a slightly better relationship is seen between the former and the second highest peak hour. All of the maximum statistics including June and later months show lower average values in 1981-1982 than 1979-1980. The median ratio and 50% ratio interval width declined from 1978-1982 for most of the maximum statistics. This reflects a reduction in variance in the underlying data sets where the peak to mean ratios dropped due to less spread.

5.1.3.2 Gridded Exposure Calclulations

The five maps presented on the following pages (Figures 5.1.1, 5.1.2, 5.1.3, 5.1.4, and 5.1.5) are the May-September assessments for 1978-1982. This period was selected as representative of the results obtained for the other growing periods. The inset map shows the monitoring stations used in the assessment. Blanks are areas of insufficient monitoring.

TABLE 5.1.5. COMPARISON OF DIFFERENT O_3 EXPOSURE STATISTICS FROM 0900-1600.

		Season		Daily Peak		Ratios		Season Max. Hour		Ratios		Season Second Max. Hour		Ratios	
Season	Year	Avg.*	S.D.	Avg.	r**	Median†	50%‡	Avg.	r	Median	50%	Avg.	r	Median	50%
APR-MAY	1978§	42	10	53	0.97	1.26	± 0.06	117	0.47	2.68	± 0.55	103	0.52	2.43	± 0.41
	1979	39	10	49	0.97	1.26	± 0.06	96	0.54	2.34	± 0.35	86	0.67	2.19	± 0.29
	1980	42	10	52	0.96	1.23	± 0.06	101	0.49	2.34	± 0.38	88	0.66	2.10	± 0.27
	1981	40	8	50	0.96	1.22	± 0.05	97	0.45	2.31	± 0.38	86	0.57	2.08	± 0.28
	1982	44	8	54	0.94	1.21	± 0.06	99	0.62	2.20	± 0.28	89	0.60	2.00	± 0.23
APR-JUN	1978	44	10	57	0.96	1.26	± 0.05	130	0.45	2.85	± 0.51	117	0.55	2.57	± 0.39
	1979	43	10	54	0.97	1.26	± 0.06	113	0.51	2.54	± 0.39	103	0.60	2.33	± 0.33
	1980	44	10	54	0.96	1.23	± 0.06	116	0.45	2.56	± 0.44	102	0.53	2.29	± 0.33
	1981	42	9	52	0.96	1.23	± 0.05	108	0.50	2.34	± 0.38	96	0.58	2.26	± 0.31
	1982	44	8	54	0.94	1.23	± 0.06	107	0.40	2.37	± 0.35	97	0.53	2.15	± 0.28
MAY-SEP	1978	46	11	61	0.96	1.31	± 0.07	149	0.45	3.12	± 0.59	134	0.52	2.89	± 0.50
	1979	44	10	57	0.96	1.29	± 0.07	132	0.49	2.94	± 0.46	118	0.57	2.64	± 0.41
	1980	46	11	60	0.96	1.27	± 0.07	133	0.50	2.78	± 0.47	120	0.61	2.53	± 0.36
	1981	44	10	56	0.96	1.26	± 0.06	123	0.42	2.72	± 0.42	110	0.57	2.50	± 0.36
	1982	43	9	55	0.95	1.27	± 0.07	122	0.50	2.79	± 0.39	110	0.62	2.51	± 0.34
JUN-SEP	1978	46	12	61	0.96	1.32	± 0.08	144	0.47	3.01	± 0.53	129	0.56	2.78	± 0.47
	1979	44	11	57	0.96	1.30	± 0.07	130	0.52	2.89	± 0.47	116	0.60	2.60	± 0.39
	1980	47	12	61	0.96	1.28	± 0.07	132	0.55	2.77	± 0.44	118	0.67	2.50	± 0.36
	1981	44	11	57	0.96	1.27	± 0.06	121	0.43	2.60	± 0.43	109	0.59	2.45	± 0.34
	1982	43	9	55	0.95	1.28	± 0.07	121	0.55	2.79	± 0.40	108	0.67	2.52	± 0.35
JUN-OCT	1978	43	11	57	0.96	1.33	± 0.08	145	0.44	3.29	± 0.60	130	0.51	3.01	± 0.51
	1979	41	11	54	0.97	1.31	± 0.08	131	0.51	3.17	± 0.54	117	0.58	2.83	± 0.47
	1980	44	11	57	0.96	1.29	± 0.07	134	0.50	3.04	± 0.52	120	0.60	2.77	± 0.44
	1981	41	10	53	0.96	1.28	± 0.06	121	0.44	2.89	± 0.49	109	0.56	2.61	± 0.40

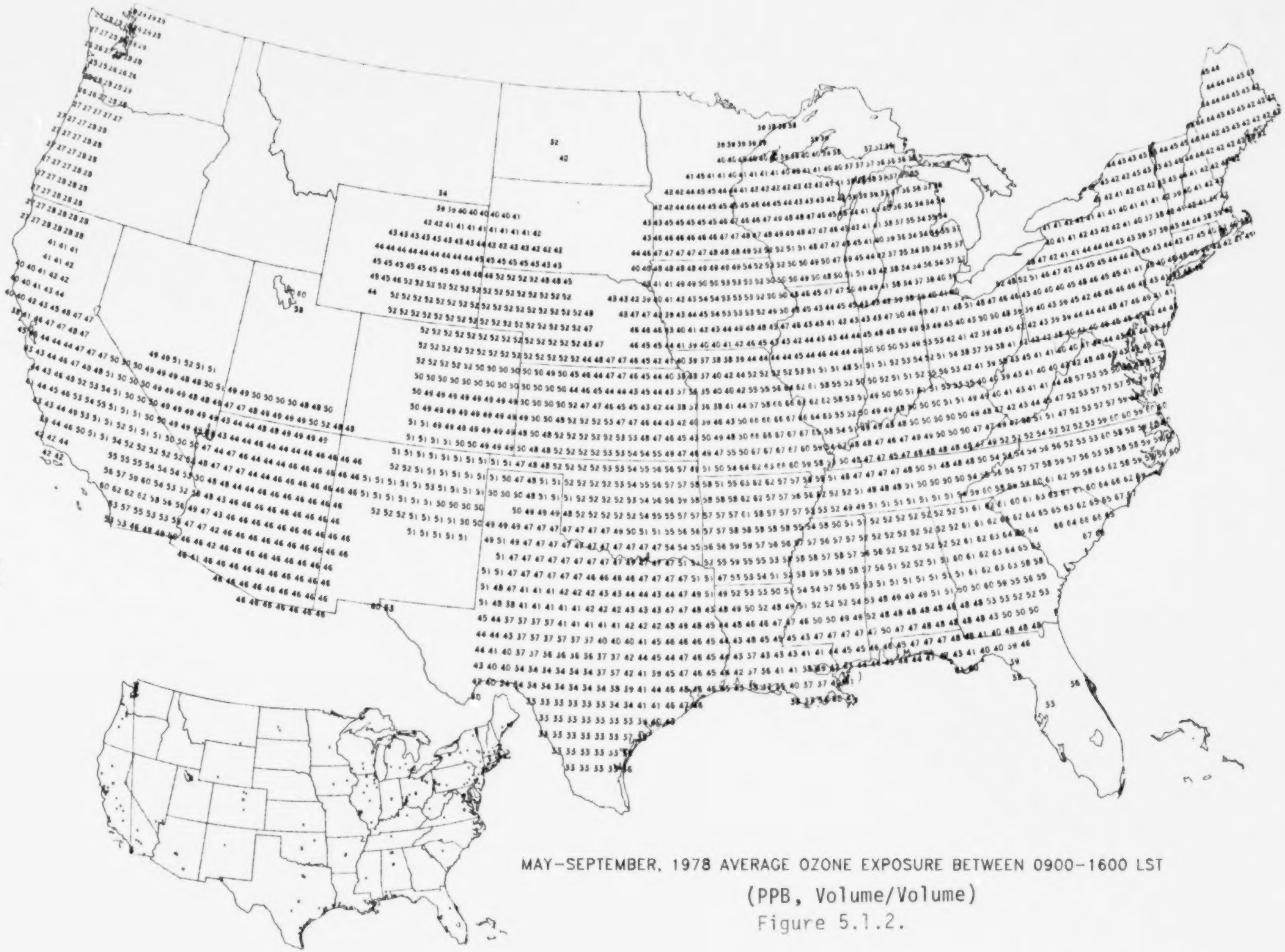
* Averages and standard deviations are expressed in parts per billion volume/volume.

** Correlation coefficient with seasonal change.

† Median of ratio statistic to seasonal average.

‡ Band around median containing 50 percent of the ratios.

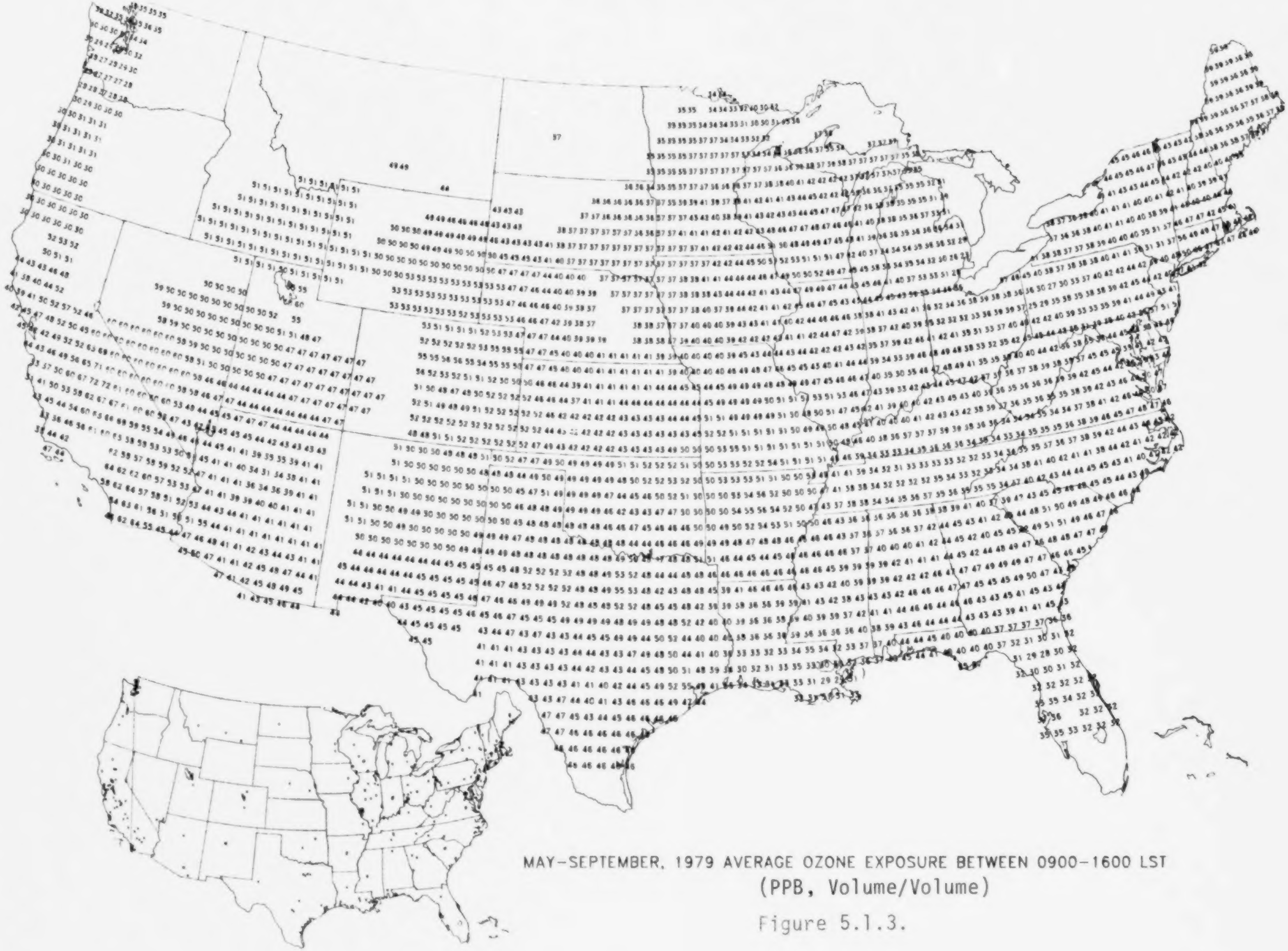
§ A change in calibration methods after 1978 inhibits comparison of 1978 with later years.


MONITORING SITES

MAY–SEPTEMBER, 1978 AVERAGE OZONE EXPOSURE BETWEEN 0900–1600 LST

(PPB, Volume/Volume)

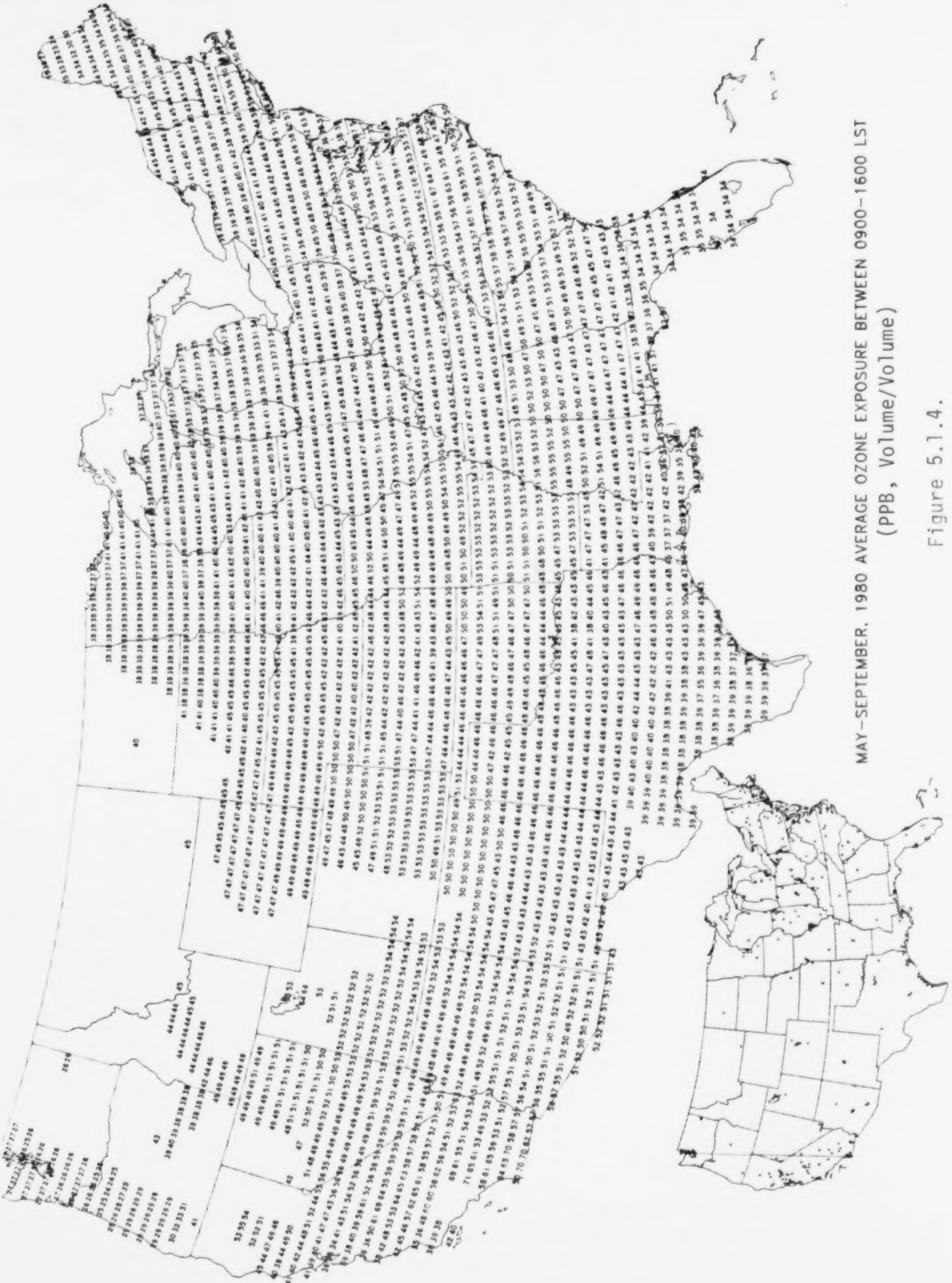
Figure 5.1.2.



MAY-SEPTEMBER, 1979 AVERAGE OZONE EXPOSURE BETWEEN 0900-1600 LST
(PPB, Volume/Volume)

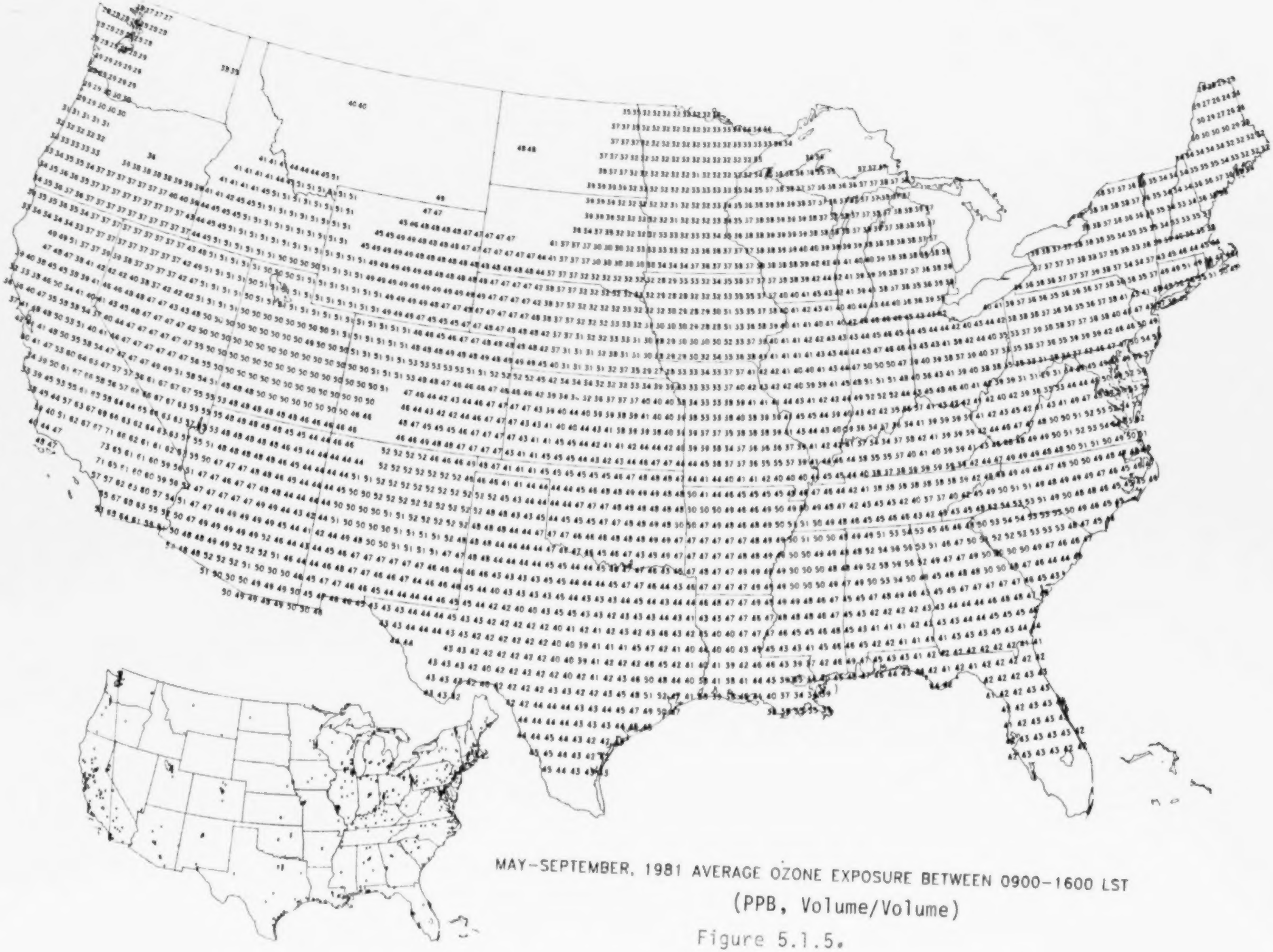
Figure 5.1.3.

MONITORING SITES

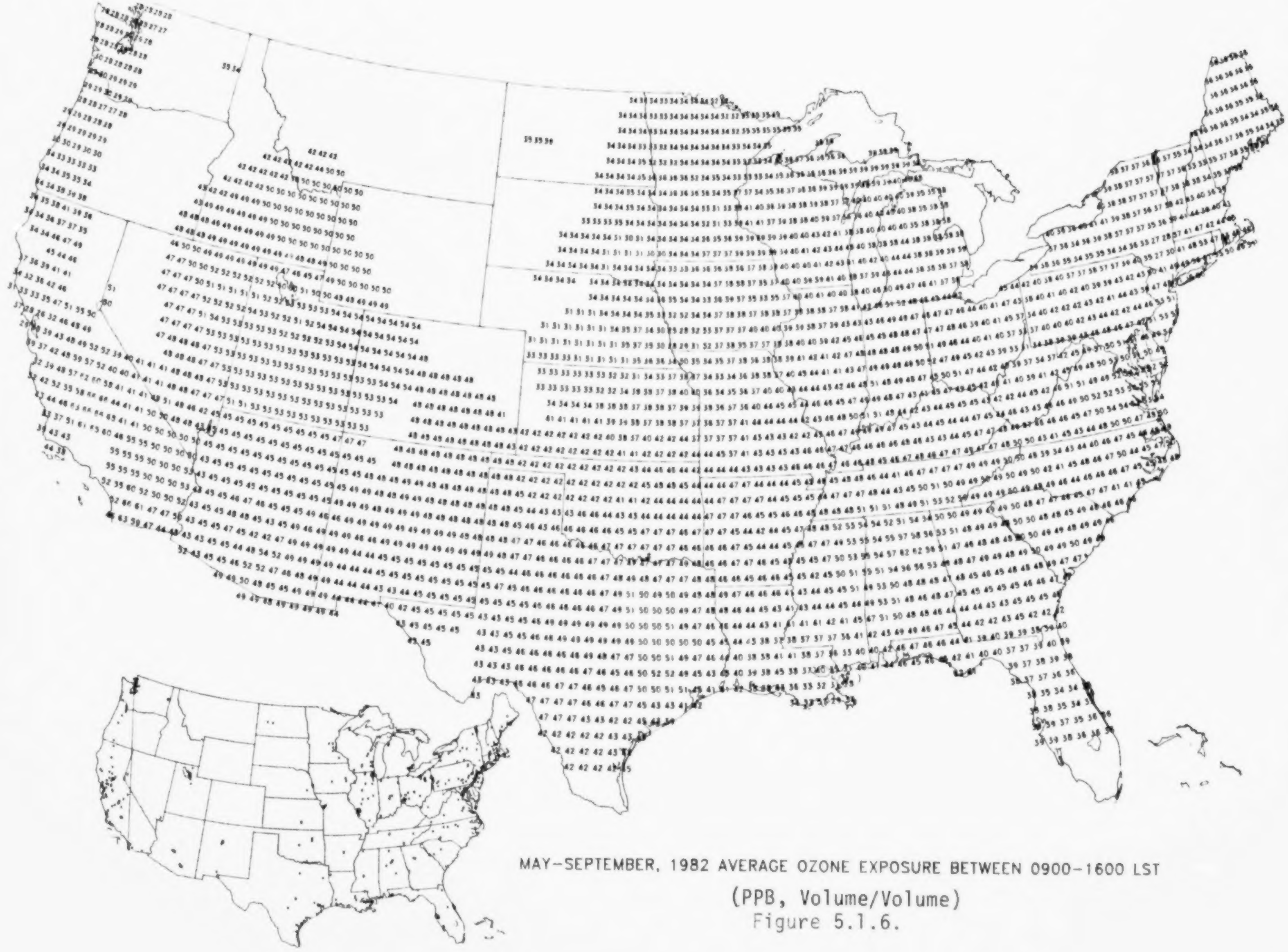

MONITORING SITES

MAY-SEPTEMBER, 1980 AVERAGE OZONE EXPOSURE BETWEEN 0900-1600 LST
(PPB, Volume/Volume)

Figure 5.1.4.


MONITORING SITES

MAY-SEPTEMBER, 1981 AVERAGE OZONE EXPOSURE BETWEEN 0900-1600 LST
(PPB, Volume/Volume)
Figure 5.1.5.


MONITORING SITES

MAY–SEPTEMBER, 1982 AVERAGE OZONE EXPOSURE BETWEEN 0900–1600 LST

(PPB, Volume/Volume)

Figure 5.1.6.

5.1.4 Discussion

Gridded estimates were presented for the continental U.S. of average O_3 concentrations between 0900-1600 LST May-September 1978-1982. Some of the seasonal exposures mentioned were converted to county level estimates. In reviewing the results the following points should be considered:

1. the average O_3 dose calculated as a point exposure at the center of a grid square is the weighted average of the five nearest qualified monitoring stations;

2. stations nearer to the estimation point have greater weights;

3. clustered stations are weighted less individually than an isolated station, distance being similar;

4. monitoring stations in excess of 500 km were not used;

5. if there were not five stations within 500 km, but one station within 30 km, that value was used for the point estimate, otherwise no estimate was made;

6. the stations are primarily urban in location;

7. monitoring values in other regions were not used across regional boundaries.

The average levels generally declined from 1978 to 1982, but this was due in part to a change of O_3 calibration methodology in 1979 which yielded a 10-20% reduction depending on technique and chance. The greater emission levels in the eastern U.S. cause higher overall levels than in the prairie states.

5.1.5 Future Work

The one feature of Kriging not yet fully incorporated into the NCLAN analysis is the error term which comes from the variogram construction and is subsequently used in the estimation. Effects of alteration of the form of the variogram equation, substitution of other intercept or nugget values, and use of the sill will be explored. Further work on the directional components for the variogram such as N-S or E-W partition may offer substantial enhancement for the error term.

A complete set of programs will be developed which will use SAROAD data as input and by stages develop gridded estimates of O_3 exposure. This system, which will be an extension of existing software, will meet exacting documentation standards, quality assurance checkout from a test data set, and be available for any other investigator. If the EPA computer center acquires one of the packages for Kriging such as COVPAC, BLUEPAC, SURFACE II, etc., then much of the system will be implemented using that package. This system will not be easily used by anyone with access to a computer. The variogram construction is unique for each data set and as of now does not permit automation, but rather usually requires several iterations. Some work will be done on developing some standard variograms which might be used. Since the number of growing seasons can be quite large by grouping different months together sequentially, the system will be constructed on a monthly basis, if possible. Equivalence of a seasonal mean with the average of several monthly means for the same period must still be tested.

Although the nearest five or ten stations has been a relatively easy criterion to implement, it may not be the best possible. For instance one could explore using all the stations within a minimum distance, development of other rationales for a maximum distance limitation, closer examination of the minimum number of stations needed, requiring some minimum directional coverage, or possibly the imposition of a longitudinal restriction for the use of stations in estimation. The work to date has only included point estimates although the theory provides for area estimates. County boundaries were too irregular to easily permit area estimates, but grid boxes lend themselves to this quite easily.

One very promising avenue of exploration is to examine the daily hour maxima distribution at sites across the county for conformity. The technique may show to what extent the urban and rural data are in conformance with one another. A second outcome may be the relaxation of the regional restrictions on data usage, especially along the continental divide.

Another area of exploration is to examine some of the LFM meteorological forecasting model output statistics relation to median O_3 maxima in station clusters. Previous work showed some correlation to the maximum values occurring in a region, but a more useful tool for rural areas could be approximations to the rural highs. A multivariate relation is established for each grid square not necessarily incorporating the same set of LFM statistics. A fairly strong regression will be necessary since the range of the median values from day to day is narrow. Assessment would entail calculations for each day for each grid square.

5.2 A MODEL ASSESSMENT OF O_3-CAUSED SOYBEAN LOSSES (SWRCLAP, Livermore, California)*

5.2.1 Introduction

Several loss estimates have been completed based on dose-response curves derived from open-top field chamber experiments (Heagle _et al_., 1980; Heck _et al_., 1982a). However, it is difficult to judge the accuracy of these estimates because of possible differences between chambers and the nation at large in (1) O_3 concentration time sequences, (b) O_3 spatial concentration gradients, (c) weather, and (d) soil water content.

Two methods have been proposed to circumvent these problems.

1. Use a scatting of paired chambers across a region to determine ambient vs charcoal filtered chamber yields. One could then construct a regression of loss vs average seasonal O_3 and other

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* David King, James Kercher, and Gail Bingham.

factors based on the paired chamber results. However, chambers are irrigated to insure more uniform growing conditions, so a chamber bias in plant sensitivity to O_3 will occur for unirrigated crops.

2. Use simulation crop models incorporating known pollutant-environment interactions to correct chamber biases and account for weather variations across a region. The assessment is produced by first calibrating the model to fit the observed chamber yield reductions and then running the model repeatedly for a number of weather and pollutant time series from the region of interest.

This report demonstrates the feasibility of using a crop simulation model to estimate regional crop losses due to air pollutants. Soybean yield losses for Illinois and Indiana were modeled to provide a comparison with a regression-based loss assessment for the same region. This assessment is described as preliminary as the model used is not yet complete, and has not been validated for a wide range of conditions. The assessment was undertaken to demonstrate the use of a simulation model for assessment. Due to severe budget and time constraints, we have been unable to include several important processes in the assessment model. These processes include soil water dynamics, O_3 gradients in the field, and threshold effects for O_3 damage. The following report demonstrates the interfacing of a calibrated model with weather and pollutant data bases, but we cannot judge the biases associated with field chamber experiments, or the magnitude of the expected overestimation of crop loss damage due to using mostly well watered treatments in NCLAN's soybean field exposures, without a more complete model.

5.2.2 The Model

In order to take advantage of past agricultural research, we have based the Soybean Yield Loss Assessment Simulator (SYLAS) on two existing crop models. We are using the soybean simulator SOYGRO developed by Wilkerson *et al*. (1981) as our basic simulator of soybean growth, development, and yield. Because SOYGRO calculates plant processes for a daily time step, we supplanted SOYGRO's photosynthesis subroutine with photosynthesis and micrometeorological subroutines from the Basic Crop Simulator (BACROS) developed by de Wit *et al*. (1978). BACROS calculates photosynthesis and conductance for individual canopy layers on an hourly basis and hence can be used to compute canopy O_3 uptake, given the hourly O_3 concentrations of the SAROAD data base as input. We have added an O_3 damage calculation to the combined models to produce SYLAS. The fundamental assumption of the model is that photosynthesis declines as a function of the cumulative uptake of O_3 by the crop. The model then translates this declining rate of photosynthesis into a yield loss, as compared with the zero O_3 simulation.

The process of model development and the rationale used for assessment are described elsehwere (King *et al*., 1982; Kercher *et al*., 1982). Important details of SYLAS are:

1. Timing of phenological events is fixed for the present.

2. The CO_2 concentration adjacent to the leaf mesophyll cells is assumed to be maintained at a constant value by the stomata.

3. The photosynthetic rate for a given leaf is determined either by light or temperature or by leaf water potential if the leaf becomes drought stressed by high transpiration rates and/or a dry soil.

4. A fixed sequence of leaf area indices (LAI's) is input to SYLAS for the first 10 days after plant emergence to correct for biases in the photosynthesis calculation for very small LAI's.

5. For the initial assessment, we have assumed that root conductance (which affects leaf water balance) is proportional to leaf area index.

6. For the present, photosynthetic efficiency of each canopy layer declines identically with whole canopy O_3 uptake.

7. Soil water content is not modeled by the current version of SYLAS. We have assumed a well watered soil for this assessment.

The O_3 Damage Calculations

Declines in both photosynthetic efficiency and photosynthetic capacity have been observed in ponderosa pine in forests exposed to pollutants from the Los Angeles Basin (Coyne and Bingham, 1982). We envision the chronic effects of O_3 on photosynthesis as being caused by cumulative damage to chloroplasts, a mechanism consistent with Coyne and Bingham's results.

The following expression is used in the model to compute photosynthesis at optimal temperature for nonstressed leaves:

$$P_n = (P_m - P_d) [1 - \exp(-ER_v / P_m)] + P_d \tag{1}$$

where P_n is net photosynthesis rate;

P_m is maximum rate of net photosynthesis at high light intensities;

P_d is dark respiration;

E is efficiency of photosynthesis (E is given by the slope of the photosynthesis vs light curve at the compensation point);

R_v is absorbed radiant flux in the 400-700 nm range.

The use of Equation (1) to estimate photosynthesis is detailed by de Wit *et al*. (1978). For the assessment, we have assumed that E declines linearly with cumulative canopy O_3 uptake. On the ith day of growth

$$E = (1 - D_i) E_o \tag{2}$$

where E_o is the unpolluted value for photosynthetic efficiency. D_i is the value of the damage function on the ith day as defined below, which reduces the photosynthetic efficiency as a function of O_3 uptake.

$$D_i = CT_i / L_i \tag{3}$$

for the first 70 days after planting

$$D_i = D_{i-1} + CU_i / L_i$$

for the rest of the season (4)

Here T_i is cumulative canopy O_3 uptake from emergence through the ith day;

U_i is canopy O_3 uptake on the ith day;

L_i is leaf area index (LAI) on the ith day;

C is a constant reflecting the sensitivity of photosynthesis to O_3 uptake.

Photosynthetic capacity (P_m) should also be a function of the damage function, and this relationship will be included in subsequent versions of SYLAS.

Cumulative uptake is divided by LAI in Equation (3) to give mean uptake per unit LAI. Equation (3) is inappropriate to compute the damage function late in the season because much of the cumulative absorbed O_3 has been taken up by senesced leaves at this time. Dividing the large cumulative uptake by the small LAI of the remaining leaves would give a spuriously high damage function late in the season. To correct this bias, Equation (4) was used to compute damage as an incremental function after the canopy reaches its maximum LAI, which happens within 70 days after planting.

SYLAS computes O_3 uptake using modeled leaf boundary and stomatal resistances. For this assessment, we have assumed the O_3 concentration in the passageways bordering the interior leaf cells to be a small fraction (∿ 10%) of the ambient concentration (see King *et al.*, 1982 for rationale). The current version of SYLAS provides a partial correction for the decline in O_3 concentration from above the canopy to the soil surface by assuming that wind speed declines as one descends into the canopy. Decreasing wind speed increases leaf boundary resistance, which in turn decreases uptake. An additional canopy resistance to O_3 uptake could easily be included in the model.

Calibrating the damage function with the field results is straightforward. One simply runs the model for the O_3 concentration time series for each treatment and adjusts C to provide the best fit to the observed yields.

5.2.3 Assessment Procedures

5.2.3.1 Model Calibration

The final 1981 soybean harvests from the NCLAN site at Boyce Thompson Institute were used to calibrate the O_3 damage function. We used all four replicates for each of the six O_3 treatments in the calibration. (The four replicates included two undisturbed chambers and two chambers which had been partially harvested for growth measurements.) We used meteorological data measured outside the chambers for the weather inputs. Use of external wind speed results in an error in the modeled leaf boundary resistance, but most of the resistance to O_3 uptake occurs at the stomata.

Before including O_3 effects, we adjusted SYLAS to fit the data for Florida soybeans described by Wilkerson et al. (1981). This version simulated yield for the 1981 Boyce Thompson experiment fortuitously well, and no changes were needed in phenology or photosynthetic response. The observed and simulated yields for the charcoal filtered treatment were within 1% of each other after calibration for O_3 damage. The modeled season length was 127 days (planting to harvest) vs 127- and 128-day seasons for the Boyce Thompson replicates. The modeled date of flower appearance was July 18 vs an observed first flowering date of July 16 for the Boyce Thompson data set.*

We first ran SYLAS using the O_3 time series observed at Boyce Thompson over the exposure period (day 51 through day 122, where day 1 is the planting date) for each of the six treatments (charcoal filtered, ambient, unfiltered, unfiltered + $\sim$ 0.030 ppm, unfiltered + $\sim$ 0.060 ppm, and unfiltered + $\sim$ 0.090 ppm). For the calibration, we assumed zero O_3 before the exposure period began, which occurred 40 days after the modeled time of emergence.** We also assumed zero O_3 for the final six days before harvest, which occurred after the treatment period. At this time, most leaves have senesced in the model runs and soybean seed development is tied to the translocation of protein products from the leaves, stems, and pod shells.

After running SYLAS for each of the six treatments, we regressed observed yield against modeled yield and adjusted the O_3 damage constant, C, of Equations (3) and (4) to obtain a slope of 1.0 for the regression of observed vs modeled yields. Because yield decline was roughly proportional to C over a wide range of values, SYLAS could be calibrated with several iterations. The correlation between modeled and observed yields was $r^2 = 0.42$ when each observed replicate was treated as a separate value. When the yields for the four replicates for each treatment were first averaged and then used in the regression, we obtained $r^2 = 0.98$. Medeiros et al. (1982) obtained the same correlation for their linear regression of yield vs exposure period dose for the Boyce Thompson data. They also averaged across replicates. Values of the important parameters of the calibrated version of SYLAS are listed in Table 5.2.1.

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* The modeled time of flowering refers to the first appearance of a flower at the node immediately below the uppermost node with a completey unrolled leaf.

** The assumption of nonzero O_3 early in the season does not greatly change the calibration of the damage function. Two model runs with roughly ambient instead of zero early O_3 suggest that the damage constant would have been decreased by about 5% had the entire season's O_3 record been used in the calibration. This insensitivity to early O_3 for calibration is due to the fact that pre-exposure O_3 was identical for the six treatments and does not imply that early season O_3 has little effect on yield. (The assessment results indicate that early season O_3 significantly affects yield.)

TABLE 5.2.1. VALUES OF IMPORTANT PARAMETERS OF THE CALIBRATED VERSION OF SYLAS.

Parameters	Value
Planting date	June 3
Flowering date	July 18
Mature crop date	October 7
E (photosynthetic efficiency without O_3)	0.5 kg CO_2 $Joule^{-1}$ ha^{-1} hr^{-1} m^2 s
P_m (maximum rate of photosynthesis)	30 kg CO_2 ha^{-1} hr^{-1}
C (O_3 damage function constant)	3.86 m^2/g O_3
Internal CO_2 concentration at air-mesophyll interface	210 ppm
External CO_2 concentration	330 ppm
Leaf angle distribution	spherical -- all orientations equally likely

5.2.3.2 Assessment

Two national data bases were used for the assessment. Hourly O_3 concentrations were input from the SAROAD data base. Hourly weather values from SOLMET were converted to daily values for radiation, maximum and minimum temperature, maximum dewpoint temperature, and mean wind speed. A relationship between daily global radiation and daily photosynthetically-active radiation (PAR) derived from the Florida data used by Wilkerson et al. (1981) was used to convert input radiation into PAR, as required by SYLAS. No precipitation values were needed, since the current version of SYLAS does not track soil water.

The assessment for Illinois and Indiana was run using 1978 data, since the 1978 SAROAD records have been checked for reliability (Reagen, personal communication). We first ran SYLAS without O_3, using 1978 SOLMET data sets for Indianapolis, Indiana; Madison, Wisconsin; and Columbus, Ohio. The number of SOLMET stations was rather low for 1977-1981, but we believe adequate for the no-soil-water-stress assessment. (We have since acquired a data set with precipitation values for a much denser grid of stations.)

To simulate yield with O_3 we used only those SAROAD stations which were used by Reagan (personal communication) in his calculation of average seasonal O_3 for 1978. These stations were situated in both rural and urban locations. We further restricted ourselves to stations having at least one-half month's data for each of the months of July, August, and September. Most of the SAROAD stations used were missing no more than 15% of the hourly values over the soybean growing season. As with the calibration runs, missing values were replaced with values from previous days. All SAROAD stations within Illinois and Indiana meeting the above specifications were used in the assessment. One Ohio and four Kentucky border stations were used to improve the representation for Indiana.

The following steps were used in the assessment.

1. Construct input data sets for each SAROAD station used. These data sets included O_3 values plus transformed weather data from the SOLMET station nearest the SAROAD station.

2. Run SYLAS for each of the input data sets generated in step 1 and for each of the three SOLMET stations without O_3. (We assumed plant uptake of O_3 began two days after emergence.)

3. Divide zero O_3 yield by ambient O_3 yield to obtain a yield enhancement factor for each SAROAD site.

4. Associate each county with the SAROAD site nearest it and multiply USDA county soybean production values by the yield enhancement factor of the associated SAROAD site.

5. Sum the enhanced production values across each economic region and divide by actual regional production to obtain zero vs ambient O_3 enhancement factors for each economic region.

This procedure was chosen as the simplest method of assessment: a background O_3 level of zero is not expected.

SAROAD stations were tightly clustered in the metropolitan areas of Indianapolis, Chicago, East St. Louis (Illinois), and Louisville, Kentucky. In these instances, yield enhancement factors were first averaged and then multiplied by county yield values. Thirty-one SAROAD stations grouped into 28 subregions were used in the assessment. (Sometimes a given SAROAD site enhancement factor was used for two or more economic regions if it lay near an economic border.) Several border counties from Missouri were included in the central and southern Illinois economic regions. Boundaries of the five economic regions were provided by Adams (personal communication).

Because the modeled yield reduction for well watered soybeans was roughly proportional to the O_3 damage constant for the calibration runs, yield will also vary linearly if a given O_3 input record is multiplied by a constant. For example, if each hourly O_3 concentration is halved, the modeled yield reduction is roughly halved. Thus, one can compute linear dose-response functions from the model results on the assumption that a change in air quality as produced by multiplying the hourly O_3 concentrations by a constant factor.* Dose-response functions and percent yield changes for ambient vs 0.035 ppm serasonal 7-h/day peak averages were calculated for the economic regions using this assumption of a linear yield response. (Dose responses were first calculated from ambient and no O_3 runs for individual SAROAD stations and then weighted by the county production values to produce regional dose-response functions.)

5.2.4 Results

Modeled changes in yield for each of the five economic regions of Illinois and Indiana are expressed as percent enhancements and depressions, repectively, in Tables 5.2.2 and 5.2.3. Linear dose-response relationships derived from the model assessment are listed in Table 5.2.4. The slope coefficients of the regional dose-responses have a range of 5% presumably reflecting regional differences in the relative peaks and valleys in the O_3 and weather data. The range in dose-response slope associated with model runs for individual SAROAD sites was larger, about 25%.

The dose-response relationship fit to the simulations for the Boyce Thompson treatments are in close agreement with the direct regression relationships between observed yield and 7-h/day average O_3 at Boyce Thopmson. Our regression relationship for the observed yields is substantially different from that of Medeiros *et al*. (1982). This difference is due to our (incorrect) assumption that missing O_3 values in the calibration data were produced by gaps in monitoring rather than gaps in O_3 generation.

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* However, as the shape of the O_3 record changes, this simple linear effect is lost. Both the shape of the record and cumulative dose may vary when assessments are made across multiple years or regions. The linear dose-response relationship may not hold when water stress effects are included in the model.

TABLE 5.2.2. MODELED YIELD ENHANCEMENT OF CLEAN AIR BASED ON 31 SAROAD STATIONS AND 3 SOLMET STATIONS, BOTH FOR 1978.*

Region	No Water Stress Assessment Results	
	Predicted Yield Enhancement Caused by Reducing O_3 to Zero**	Predicted Yield Enhancement Caused by Reducing O_3 to 0.035 ppm†
Illinois -- North	34.2%	8.5%
Illinois -- Central	35.3%	9.2%
Illinois -- South	48.3%	18.8%
Indiana -- North	41.9%	13.6%
Indiana -- South	38.2%	12.2%

* The 0.035 ppm O_3 of the right column is a June-September (inclusive) 7-h/day peak average. Yields for 0.035 ppm O_3 are calculated from no O_3 and ambient air model runs by assuming that: (1) the ambient air O_3 time sequences are scaled down to give 0.035 ppm averages; and (2) yield is a linear function of average O_3 for a given O_3 concentration time sequence. Intermediate O_3 model runs show assumption 2 to be approximately true.

** Listed enhancement = $\dfrac{\text{no-}O_3\text{ yield - ambient air yield}}{\text{ambient air yield}} \times 100\%$

† Listed enhancement = $\dfrac{0.035\text{ ppm }O_3\text{ yield - ambient air yield}}{\text{ambient air yield}} \times 100\%$

TABLE 5.2.3. YIELD ENHANCEMENTS OF TABLE 5.2.2 EXPRESSED AS DEPRESSIONS DUE TO AMBIENT VS CLEAN AIR.

Region	Yield Depressions Compared to No-O_3 Yield*	Yield Depression Compared to 0.035 ppm O_3 Yield**
Illinois -- North	25.5%	7.9%
Illinois -- Central	26.1%	8.4%
Illinois -- South	32.6%	15.8%
Indiana -- North	29.5%	12.0%
Indiana -- South	27.6%	10.9%

$$* \text{ Listed depression} = \frac{\text{no-}O_3 \text{ yield} - \text{ambient air yield}}{\text{no-}O_3 \text{ yield}} \times 100\%$$

$$** \text{ Listed depression} = \frac{0.035 \text{ ppm } O_3 \text{ yield} - \text{ambient air yield}}{0.035 \text{ ppm } O_3 \text{ yield}} \times 100\%$$

TABLE 5.2.4. LINEAR RELATIONSHIPS BETWEEN PRECENTAGE SOYBEAN YIELD LOSS AND SEASONAL 7-H/DAY PEAK AVERAGE DERIVED FROM THE MODEL ASSESSMENT.*

Region	Model Derived Dose-Response	Predicted Percent Losses with the Listed Seasonal 7-h/day Peak O_3 Averages in ppm		
		0.045	0.055	0.065
Illinois -- North	$y = -21.4 + 610x$	6.1	12.2	18.3
Illinois -- Central	$y = -21.4 + 613x$	6.1	12.3	18.4
Illinois -- South	$y = -20.2 + 576x$	5.8	11.5	17.3
Indiana -- North	$y = -21.3 + 609x$	6.1	12.2	18.3
Indiana -- South	$y = -20.1 + 575x$	5.8	11.5	17.3
Regression Fit to Modeled Boyce Thompson Yields (Ithaca, New York)	$y = -15.5 + 443x$**			
Regression Fit to Observed Boyce Thompson Yields	$y = -16.2 + 464x$**			

* Y is the percent yield depression relative to a crop grown at a seasonal 7-h day peak O_3 average of 0.035 ppm. X is the seasonal O_3 average for hours 9-16 of July through September. The expressions for Illinois and Indiana are derived from modeled yields for ambient vs no O_3. All six treatments were used in the regression of the Boyce Thompson model results: this regression was constrained to fit the relative yield of the no O_3 model run. The direct regression relationship for Boyce Thompson was derived from a least squares fit of observed yield vs 7-h/day average peak O_3 over the exposure period (July 23 to October 2).

** The Boyce Thompson yield regressions wee derived from mean rather than peak 7-h/day O_3 averages. The slopes of these regressions would be slightly lower had the higher peak averages been used.

The assessment derived regression relationships for Illinois and Indiana give yield reductions 30% greater than those associated with the direct dose-response regression for Boyce Thompson. This difference is due mainly to the fact that the assessment incorporates O_3 uptake occurring over a 38-day interval preceding the exposure period at Boyce Thompson. A model simulation with and without early season O_3 suggests that O_3 occurring before the Boyce Thompson exposure period accounts for about 1/3 of the assessed yield loss.

So far we have presented only relative values for the economic regions. Observed vs modeled yields are shown in Table 5.2.5, as well as the fortuitously close agreement between modeled and observed yields for Boyce Thompson. Modeled yields are twice the observed yields, reflecting (a) suboptimal rainfall; (b) nonoptimal planting dates and fertilization; (c) pests and pathogens; (d) weed competition; (e) harvest losses; (f) other cultural practices; and (g) possible errors in the model temperature and humidity response. The model was calibrated with intensively managed plots which typically have much higher yields than commercially grown crops. Thus, the model initially calibrated with Florida experimental plot data agrees with Boyce Thompson experimental yields, but is high compared with commercial yields. Some of the factors depressing field vs modeled yields, such as water stress, may also alter the percent loss caused by O_3. Those factors which interact with pollution must be included in the model to provide a valid loss assessment. Temperatures were higher for the 1978 Illinois-Indiana assessment than for the calibration experiment, contributing to the high simulated LAI for this region (Table 5.2.5).

5.2.5 Discussion

We have presented a simulation assessment of O_3-caused yield losses to soybeans based on the premise that losses are caused by cumulative O_3 uptake. This trial assessment demonstrates that properly constructed simulation models can be used in national crop loss assessments given existing data bases, or additional data which can be collected at NCLAN field sites with little extra effort. The present assessment is useful in establishing the relationships that exist between environmental conditions and crop loss. These relationships are detailed in the following paragraphs. Of most significant interest is the close agreement between crop loss estimates for well watered plants using either the regression or simulation approaches, once differences between experimental and field exposure times are corrected in the regression approach. This agreement suggests that an assessment accounting for pollutant exclusion due to water-stress-reduced stomatal conductance would result in significantly reduced crop loss estimates.

In this purposely simplified assessment, cumulative uptake is assumed to have a direct effect on photosynthetic efficiency, an effect which is translated into a yield loss by the soybean growth simulator. We have focused on relative yield loss (Δ yield/yield) in both the calibration of the soybean yield loss assessor (SYLAS) and in the assessment itself. Simulated yields for the assessment vs calibration runs for Boyce Thompson differed by a factor of nearly 1.5 (Table 5.2.5). However, simulation derived dose-response relationships (expressed as percent losses) are similar if differences in the modeled exposure time are accounted for. The difference in modeled yields for assessment vs calibration runs is probably due to differences in temperature; we assumed well watered crops in both cases.

TABLE 5.2.5. MODELED VS OBSERVED MEAN YIELDS IN BUSHELS/ACRE.*

Region	Modeled		Observed	
	Max. LAI	Yield	Yield	Yield Range
Indiana -- North	6.14	65.1	35.2	27.1 - 42.7
Indiana -- South	6.20	66.7	31.7	21.9 - 36.5
Boyce Thompson (charcoal filtered treatment)	4.34	47.0	47.4	39.0 - 67.3

* Illinois regional yields are similar to the Indiana yields shown here. Modeled dry weights were converted to bushels/acre assuming 60 lb/bushel at a 13% water content.

Relative yield losses were calculated in terms of yields associated with 0.035 ppm seasonal peak 7-h/day O_3 averages. Caution is required in interpreting such relative yield losses because of our assumption that the 0.035 ppm clean air average results from multiplying each ambient concentration time series by a constant factor. O_3 peaks attributed to natural causes occur under quite different weather conditions than do anthropogenic O_3 peaks (Derwent et al., 1978).

The model based assessment may be superior to regression based assessments because it includes early season O_3 and because it accounts for variation in the timing of O_3 concentrations and weather inputs affecting O_3 uptake. The results suggest that regression of observed yield vs average field chamber O_3 can be corrected for early season O_3 by multiplying them by a factor,

$$f = \frac{\text{soybean season length}}{\text{chamber exposure period}}$$

Because the main thrust of this work has been to demonstrate the feasibility of a model based assessment, we have left a number of factors unaccounted for. These factors are involved in the two-fold difference between observed and predicted yields for the assessment regions. We believe that the influence of water stress on O_3 uptake is the most important factor yet to be included in SYLAS. The present version of the model assumes a well watered soil and is conservative in assessing the effects of vapor pressure deficit on conductance. Our observations on soybeans and those of other groups (Acock, personal communication) suggest that stomatal conductance may be water limited at intermediate temperatures and humidities for well watered soybeans under sunny conditions. (The present model limits conductance in the upper canopy only for high temperature, low humidity, and high sunlight if the crop is well watered.)

Our analysis of the effect of soil water potential on conductance indicates that drought may have a large effect on O_3 uptake, an effect which depends on the hourly variation in O_3 concentration throughout the day (King et al., 1982). We also anticipate an interaction between O_3 damage and water use. If a plant experiencing a midseason drought has been previously damaged by O_3, it will have lower rates of photosynthesis and transpiration than an undamaged plant, thus using water at a slower rate. As a consequence, the total yield reduction due to drought plus O_3 will be less than the sum of the losses due to each factor acting independently.

Krupa and Teng (1982) have questioned the use of SAROAD values measured at a height of 3 m as an estimate of within canopy O_3 concentration. Chamber O_3 concentrations are quite uniform because air is forced through the sides of the canoy and out the chamber top. Measurements of ambient O_3 concentration gradients by Heagle (personal communication) indicate that subcanopy O_3 concentrations may be 60 to 95% of 3 m values, depending on soil surface wetness, wind, and height in canopy. We believe that incorporation of O_3 gradients by SYLAS (via a canopy transfer resistance) will contribute to a defensible assessment.

Our calculation of O_3 damage to photosynthesis assumes that damage is proportional to cumulative O_3 uptake, independent of variations in the rate of uptake. If plants can denature the damaging radicals derived from absorbed O_3, then a threshold response is expected (King et al., 1982). In this case absorbed O_3 is denatured before damaging chloroplasts when the uptake rate is low. The model prediction of a 15 to 16% yield reduction for 0.035 ppm vs no O_3 suggests that background O_3 may select for plants with an ability to detoxify O_3. Inclusion of a damage threshold in the model will lower yield loss predictions for ambient vs no O_3. Similar losses to those reported here are expected for ambient vs 0.035 ppm O_3, since the model with a damage threshold would be calibrated with the same experimental data. More importantly, a greater fraction of the damage to photosynthesis would be caused by periods of high O_3 uptake, possibly increasing the variability in dose-response between economic regions.

Other possible sources of error in the assessment could be addressed by an analysis of the sensitivity of the modeled dose response to changes in planting date, phenology, and season length. A partial analysis of varietal differences in plant sensitivity to O_3 could be accomplished by calibrating the model for the different varieties grown at different NCLAN sites for different years and running the variably calibrated versions with a common input data set. In this fashion, varietal effects can be distinguished from the effects of variation in weather and O_3 time series between experiments.

Recent NCLAN experiments directed by H. Heggestad (soybeans) and O. C. Taylor (cotton) (see Section 4.4) have included water stress-pollutant treatments. Such experiments would provide an excellent means of validating and calibrating a complete assessment model. However, water stress experiments cannot be used directly for assessment unless each pollution treatment receives equal amounts of water. If, instead, soil water content is maintained at a constant value across treatments, then the effect on yield of differences in the rate of water use between pollutant treatments is not accounted for. As noted previously, water stress not only affects pollutant uptake, but pollutant uptake affects the rate of water use by the crop. A model based assessment accounting for differences in the timing of drought and differences in the correlation between drought and O_3 is the logical assessment procedure.

We note that the Basic Crop Simulator used by SYLAS to compute O_3 uptake is a general crop simulator. Biases in yield loss estimates due to water stress and other factors may be similar for a number of crops. A model based assessment for soybeans plus a sensitivity analysis of important factors may therefore be of value in judging the accuracy of regression based dose-response functions for all crops.

5.3 THE NCLAN ECONOMIC ASSESSMENT PROGRAM

5.3.1 Introduction

Previous annual reports and articles (Heck et al., 1982a, 1982b) have discussed the objectives and procedures of the NCLAN economics program. The primary objective of the NCLAN economics program remains the assessment of the national economic consequences of ambient O_3 on agriculture. This section reports on progress to date in meeting this objective. Specifically, this section describes the growing body of economic data and experience which have been gained through the NCLAN program and the implications of these findings for performance of a preliminary national assessment of O_3 damages in 1984.

The analyses and results from 1982 focus on an important issue in performing economic assessments, namely the sensitivity of economic assessments to uncertainties in the biological data and the implications of that sensitivity in terms of generating credible economic estimates. The question to be addressed is how will the planned national assessment benefit from additional types of biological information on plant response? Preliminary evidence is available from the 1982 program with which to partially answer the question. Specifically, the issue received considerable attention with the initiation of regional mathematical programming-based economic assessments which were subjected to sensitivity analyses. In addition, two statistically based studies were initiated that also partially answered the question. This section discusses these 1982 programming and statistical analyses as well as the anticipated 1983-84 preliminary national economic assessment effort.

5.3.2 1982 Results -- Identifying and Quantifying the Effects of Biological Uncertainty on Economic Estimates

There are various sources of uncertainty arising from the dose-response measure which may affect the economic assessments. There are at least three types of uncertainty which may be of consequence: (1) natural uncertainty, or uncertainty about the physiological process being studied, such as the exact manner in which a plant metabolizes each molecule of a toxin; (2) statistical uncertainty, or the doubts due to limited data, associated with estimation of the parameters of any particular model of this physiological process; and (3) model uncertainty, or the misgivings about whether a particular model of the physiological processes is the "true" model. An example source of uncertainty might be the potential interaction of soil moisture stress and O_3. Uncertainty arising from this interaction may occur under (1) or (2) above. Not all sources of uncertainty can be eliminated nor is it necessary to do so to develop efficient policies. What is needed, then is some means of discriminating among these sources as to which is most critical to the use of the dose-response information in performing assessments. Within the context of "value of information" theory, acquisition of information on these critical sources is worthwhile if (1) it will be used in the decision process and (2) the benefits of the improved information exceed the costs of acquiring that information.

Four studies were initiated in 1982 which attempt to measure the consequence of such variability in the biological data (dose-response measures) on economic estimates. Several of these studies were discussed in the 1981 annual report (Heck *et al.*, 1982b). Completion dates for all studies is September 1983. These studies include:

1. A study of Corn Belt agriculture using a series of 13 mathematical programming models representing "typical" farms in this 5-state region (Illinois, Indiana, Iowa, Ohio, Missouri). In the preliminary farm level analysis, changes in farm income arising from various O_3 levels and yield assumptions were estimated, with

projected change in income being somewhat unresponsive to O_3 levels if farmers were allowed to adjust cropping patterns. In the analysis, adjustments in crop mixes and acreage serve to offset potential yield reductions due to worsening in air quality. The validity of these observations depends on the producers ability to recognize O_3 effects. In the second phase of this analysis, these results are entered into an aggregate or macro model linking regional production with national consumption (demand). The output from the macro model conveys the effects of yield changes on consumer well-being. Final results describing total regional impacts as measured through the macro model were completed in June 1983 and are reported in Brown and Pheasant (1983) and McCarl *et al.* (1983). This same macro model was then subjected to a range of sensitivity analyses to record the effect of different dose-response information on economic estimates. The results, as reported in Adams and McCarl (1983) indicate the importance of resolving certain interactive effects between O_3 and other stress factors.

2. A study of California agriculture using a regional level programming model of annual and perennial crop production. As in the Corn Belt study, extensive sensitivity analyses were performed to test the effect of variability in dose-response, in terms of cultivar selection, sample size, and model specification, on the economic estimates produced by the economic model. Final analyses will be completed by September 1983.

3. A statistically-based analysis of model uncertainty as measured by alternative functional specifications on economic estimates for the Corn Belt for three major crops (corn, soybeans, and wheat). This study indicates that model specification and resultant differences in yield response will cause slight to moderate variation in the economic estimates. While the variability in economic estimates arising from the use of two dose-response models (linear and Weibull) results in approximately a 30 percent difference in economic estimates, it does not alter the rank ordering of economic estimates for respective discrete O_3 assumptions. That is, economic benefits at 0.04 ppm > 0.05 > 0.08 ppm seven hour O_3 concentrations. Thus, the variability due to model change would probably not influence the selection of economically efficient O_3 levels.

4. A statistically-based analysis of the impact of yield variability on economic estimates of losses to four major commodities (corn, cotton, soybeans, and wheat). This "value of information" analysis focused on only one source of yield variability, sample size. Preliminary results suggest that the experimental design as measured by number of observations (chambers), is adequate to provide usable dose-response information for an aggregate economic assessment. The study does not resolve errors which may arise from extrapolation of the yield responses to other cultivars, regions, or soil-moisture conditions. This source of variability may be substantial and is partially addressed in ongoing assessments discussed ion Section 5.3.4.

The last two studies were completed prior to the preparation of this annual report. Observations and discussions from these studies are highlighted in the following section.

5.3.3 A Comparison of Economic Losses Using Alternative NCLAN Response Models

The analysis is based primarily on data reported in the 1981 Annual Report (Heck et al., 1982b). Using these NCLAN data, response functions are estimated using alternative response models. The results indicate that predicted yield response varies across models and that discrimination by means of standard statistical measures may not always provide unequivocal answers. The variation in yield responses suggests that the use of these different response models may effect the economic assessments for which they are intended. It is the purpose of this section to implicitly test this hypothesis by estimating economic effects of O_3 using two of these alternative models, the linear and Weibull.

An economic model is briefly discussed and implemented that accounts for the effect of yield reductions as suggested by the alternative NCLAN response functions on consumer and producer well-being. Economic estimates of losses (or benefits of control for reductions below current ambient levels) are then derived from the economic model for a specific region using potential yield and production adjustments predicted by the dose-response models at alternative O_3 levels.

The emphasis here is on demonstrating general procedures and issues and not the development of definitive measures of the economic benefits of O_3 control. The ultimate validity of these economic estimates is dependent on their sensitivity to the incorporated economic, biological, and air quality data and the resultant economic estimates should be caveated accordingly.

5.3.3.1 Procedure

The procedure encompasses two distinct steps. First, physical adjustments in production (as measured in 1000 metric tons) are predicted for a set of major agricultural commodities associated with alternative air quality (O_3) assumptions. The predicted reductions are derived from the NCLAN response data for specific crop cultivars using alternative response models. Second, the physical losses are used to drive the economic model, which provides estimates of the direction and magnitude of economic losses associated with these alternative air quality levels. Thus, the response data are critical inputs for the economic assessment.

The analysis covers three major commodities for which NCLAN data are available: corn, soybeans, and wheat. The area of interest is the Corn Belt (Ohio, Indiana, Illinois, Iowa, and Missouri), a major production area for these crops that is also subject to relatively high O_3 concentrations. This region produces approximately 35 percent of U.S. corn and soybean production and 10 percent of wheat production (USDA, 1981).

The assessment analyzes three assumed air quality levels as well as a base situation reflecting ambient concentrations. Specifically, these include a seasonal seven-hour mean concentration of 0.04 ppm, 0.05 ppm, and 0.08 ppm and actual (1980) O_3 levels. The first level (0.04 ppm) portrays an improvement in air quality for all states and sub-regions in the Corn Belt from current (1980) levels as reported in USEPA SAROAD data. The level of 0.05 ppm, on average, represents a slight improvement in regional air quality. The extreme level of 0.08 ppm depicts a rather severe worsening of air quality. In addition to each of these levels, current levels of air quality and production are used to calculate a base case against which these standards may be compared.

Sub-state level air quality and crop production data form the basis of the physical loss assessment. Specifically, the 5 states in the Corn Belt are disaggregated into 13 sub-regions intended to portray homogenous production areas. Cropping pattern alternatives, resource availability, and air quality (as established by J. Reagan through use of SAROAD data) are assumed constant within each sub-region. These sub-regional data, when combined with NCLAN response data using both the linear and Weibull loss models for a representative cultivar (where more than one is available) for a given region, provide yield loss and production adjustments for use in the economic model. Each of the key data sets and assumptions are discussed in more detail below.

5.3.3.2 Economic Model

The economic framework used here addresses some, but not all, economically important issues underlying this type of environmental problem. These issues have been reviewed in past NCLAN publications and reports. Specifically, the incorporated economic model accounts for price adjustments which may arise with changes in crop production due to O_3 and measures the effect of such price changes on consumer and producer well-being.* This measure of well-being, known as economic surplus, portrays in dollar terms the net welfare associated with the production-consumption of alternative levels of the commodities in question. While this concept is somewhat abstract, its use in policy analysis is well documented (Mishan, 1964, 1971; Just *et al.*). By comparing the economic surplus at respective supply-demand intersections (for each air quality level) with the base case or current levels, the potential changes in net benefits/costs for each O_3 level may be assessed. Measures of (changes in) economic surplus are used in this analysis to indicate the benefits of pollution control.

Through the integration of the area defined by the intersection of the crop supply and demand equations, the economic model allows the calculation of price (changes) associated with various supply-demand quantities for each commodity. This integral can be approximated geometrically using the linear supply and demand parameters and the corresponding equilibrium quantity. For this analysis, a simple computational algorithm was employed to determine the economic surplus for each crop at each assumed O_3 level.

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* The key features of the economic model are discussed in a forthcoming journal article (Heck *et al.*, 1983).

5.3.3.3 Response Estimation

For soybeans, corn, and wheat, more than one cultivar was available from the multiple years of the NCLAN program, specifically, seven cultivars of soybeans, seven of wheat, and three of corn are available from the NCLAN experiments. For each region, a representative cultivar (as measured in percentage of acreage in a region) was selected from the set of available cultivars.

The specification of an appropriate functional form to portray the nature of yield response to dose is important to both physical and economic assessments of loss. The statistical results of alternative functional specification (linear-plateau, Weibull, quadratic) indicates that forms other than the linear may provide better predictors of yield response to O_3 dose for some crops. If the predicted yield responses differ sharply across specification, the economic assessments may also vary. To test this, the economic assessments were performed using both linear and Weibull loss models. The response of some crops display sensitivity to functional form. This is exemplified by corn, where a linear model predicted much higher losses than the Weibull. If the linear predictions are not consistent with biological considerations, the linear model would then provide measures of economic loss which may be misleading.

5.3.3.4 Air Quality Data

Knowledge of current ambient O_3 levels is needed to establish base case production levels for each state and region. That is, all yield adjustments and aggregate production responses for a given region are expressed in terms of changes from an assumed base case. Thus, if a region has relatively low O_3 concentrations, movement to a seven-hour seasonal mean level of 0.04 ppm will imply a smaller increase in yields than for a region with relatively higher O_3 concentrations. Since the economic assessments (for each air quality assumption) are based on comparisons with the current case (1978-1980 average production, 1980 air quality), it is important that the base case data be representative of the relative regional air quality levels.

The air quality data used here are derived from USEPA SAROAD data, as modified by USEPA researchers (see Section 5.1). Modification was needed to approximate rural air quality from primarily urban monitoring sites. This required interpolation as well as some extrapolation to fill data gaps for all major crop-producing areas. The appropriateness of these modifications and the resemblance of O_3 estimates to ambient rural O_3 levels is important to the physical loss estimates used to drive the economic model. Initial validation of these estimates against actual O_3 levels reveals a high degree of correspondence.

5.3.3.5 Results

Using the regional level air quality data and the linear and Weibull response models developed earlier, potential changes in crop production associated with varying air quality assumptions were calculated. An averaged base production level was used to minimize the likelihood of selecting an unrepresentative or atypical production year upon which to base the analysis.

The base case refers to the 1978-1980 average production of each commodity. The actual (ambient) and potential production levels for each commodity for each functional specification are presented in Table 5.3.1.

The average production levels serve to define the base case economic surplus levels, using the economic model defined earlier. By then using the assumed production levels (equilibrium quantities) from Table 5.3.1 under the alternative air quality levels (0.04, 0.05, and 0.08 ppm), new values for economic surplus are calculated. The difference between the 0.04 and 0.05 values and the base case approximate the economic benefits of control at the alternative air quality levels. The 0.08 ppm value represents costs of a degradation in air quality. The economic surplus estimates and the differences (between base case and alternatives) are presented in Table 5.3.2.

As is evident from the table, the benefits of improved air quality on agriculture increase as O_3 concentrations decline. At a concentration of 0.04 ppm, the societal benefits (of O_3 reductions below 1980 ambient levels) in terms of these three commodities for the Corn Belt are approximately $0.7 billion with the linear models and $1.2 billion with the Weibull model. The 0.05 ppm concentration is relatively close to ambient for most regions and results in approximately a $0.13 billion benefit with the linear and $0.23 billion with the Weibull. For those O_3 levels, the use of the Weibull model results in substantially greater benefits of control than the linear specification. However, the opposite case is noted for the 0.08 ppm analysis. Here, societal well-being is estimated to be reduced by $3.1 billion according to the linear models and $2.9 billion for the Weibull. This reversal in relative effects in the linear case arises primarily from corn, which, in keeping with linear-plateau specification is insensitive to O_3 at ambient levels but is moderately sensitive at accelerated O_3 concentrations. Conversely, with the Weibull, modest yield changes are recorded throughout the O_3 levels. Had a strictly linear response function been used for corn, the differential would have been much more dramatic (the loss estimate would be over $2 billion greater for the linear). As a proportion of total or aggregate value associated with base level production, the benefits of control from ambient to 0.04 ppm would be about 5 to 8 percent of Corn Belt totals. Losses associated with degradation from ambient to 0.08 ppm amount to approximately 20 percent of current Corn Belt values for each model. The implication is that, for some crops, any statistical discrimination among response functions needs to be tempered with biological input before use in economic assessments. These results also imply that experimental data (observations) need to be designed to adequately cover the response surface so that statistical discrimination will be enhanced.

The results of this economic assessment procedure need to be placed in perspective. Besides abstracting from production adjustments in regions outside the Corn Belt, it should be noted that the framework is unable to account for producer mitigative adjustments such as substitution of cultivars or crops, locational adjustments, changes in input usage, and other management strategies that may alter potential economic losses. Such adjustments could, however, be handled in other economic procedures such as the mathematical programming approach being used in the NCLAN national assessment. The emphasis here is on capturing price effects and their implications for consumers and producers of agricultural commodities. In this, as well as most

TABLE 5.3.1. ACTUAL AND PROJECTED CORN BELT PRODUCTION UNDER ALTERNATIVE O_3 LEVELS.

Crop	Ambient Production (1978-80 Average production)	Projected Changes in Producton for Alternative O_3 Levels 0.04 ppm Linear*	0.04 ppm Weibull	0.05 ppm Linear*	0.05 ppm Weibull	0.08 ppm Linear*	0.08 ppm Weibull
				1000 tons			
Corn	112,553.90	0.00	2068.70	0.00	401.81	-8,554.00	-10,179.71
Soybeans	32,363.80	2041.05	1501.82	370.53	284.00	-4,641.05	-3722.94
Wheat	6,574.20	220.90	88.52	48.66	24.28	-468.07	-335.20

* Linear response models for soybeans and wheat, linear-plateau for corn.

TABLE 5.3.2. ECONOMIC SURPLUS FOR ACTUAL AND PROJECTED CORN BELT CROP PRODUCTION AT ALTERNATIVE O_3 LEVELS.

Crop	Economic Surplus for Ambient Air Production	Change in Economic Surplus					
		0.04 ppm		0.05 ppm		0.08 ppm	
		Linear	Weibull	Linear	Weibull	Linear	Weibull
	$ Billion						
Corn	33.849	0.000	0.691	0.000	0.134	-1.650	-1.804
Soybean	9.170	0.649	0.468	0.115	0.090	-1.374	-1.082
Wheat	10.273	0.079	0.030	0.017	0.008	-0.152	-0.109
Total	53.292	0.728	1.189	0.132	0.230	-3.136	-2.995

other economic procedures, the yield changes depicted by response information serve to start the economic mechanisms in motion. The ultimate economic effect of these yield reductions may be less apparent than the triggering yield reductions, as the economic responses may dampen or exacerbate the physical response.

5.3.4 The Impact of Enhanced Precision in Yield Response Estimates on Economic Assessments

The intent of this Bayesian statistical analysis is to measure the entire probability distribution of economic estimates of benefits or losses occurring at alternative O_3 levels, not just the expected value of these estimates reported in the previous analysis. Procedures and assumptions are discussed in more detail in Adams et al. (1983). Again, economic effects are measured in terms of economic surplus as defined in Subsection 5.3.2. Rather than assuming that the estimated yield response parameters are the "true" ones, statistical uncertainty associated with those parameter estimates is explicitly acknowledged by including it in the analysis. The inclusion provides insight into what can be gained by additional observations on the yield responses of corn, soybeans, wheat, and cotton to ambient O_3. Additional observations provide reductions in the variance of the yield response parameter, β, ultimately causing it to converge on some stable magnitude which approaches the true but unknown magnitude, β.

For each of the four crops, the analysis consisted of calculating the density functions of the differences in economic estimates between current regional ambient O_3 concentrations and alternative seasonal seven-hour average levels of 0.07 ppm, 0.05 ppm, and 0.04 ppm. These density functions of economic benefits and losses measured the uncertainties in economic estimates attributable to the estimated parameters of both linear and quadratic O_3 response functions. Figure 5.3.1 portrays the aggregate density functions for the four crops using a quadratic response model. Two features of the density functions are worthy of note. First, the mass of the economic estimates at and in the immediate neighborhood of their means were very great for each crop-ambient O_3 combination. Additional experiments using quadratic yield response functions for the four crops would increase the mass at the mean of each distribution, but it seems likely that this increase would contribute very little to any economic use of the estimates based on these distributions. Second, this judgment is reinforced by the general lack of overlap between distributions. This lack of overlap between distributions implies that for these discrete O_3 levels and these crops the tradeoff between Types I and II statistical error would not need be confronted, if such economic loss estimates are to be used primarily to discriminate among the economic implications of the alternative ambient O_3 levels.

These observations concerning enhanced precision in the quadratic model hold as well for a linear response specification. The distributions again display no overlap, reflecting the concentration of economic surplus estimates in the neighborhood of their means. However, for each case, the linear expected economic benefits for all O_3 levels is slightly more than the quadratic. While the choice of which O_3 level is most economically efficient would not change under either model specification, this comparison suggests that model form or specification may be potentially more important than

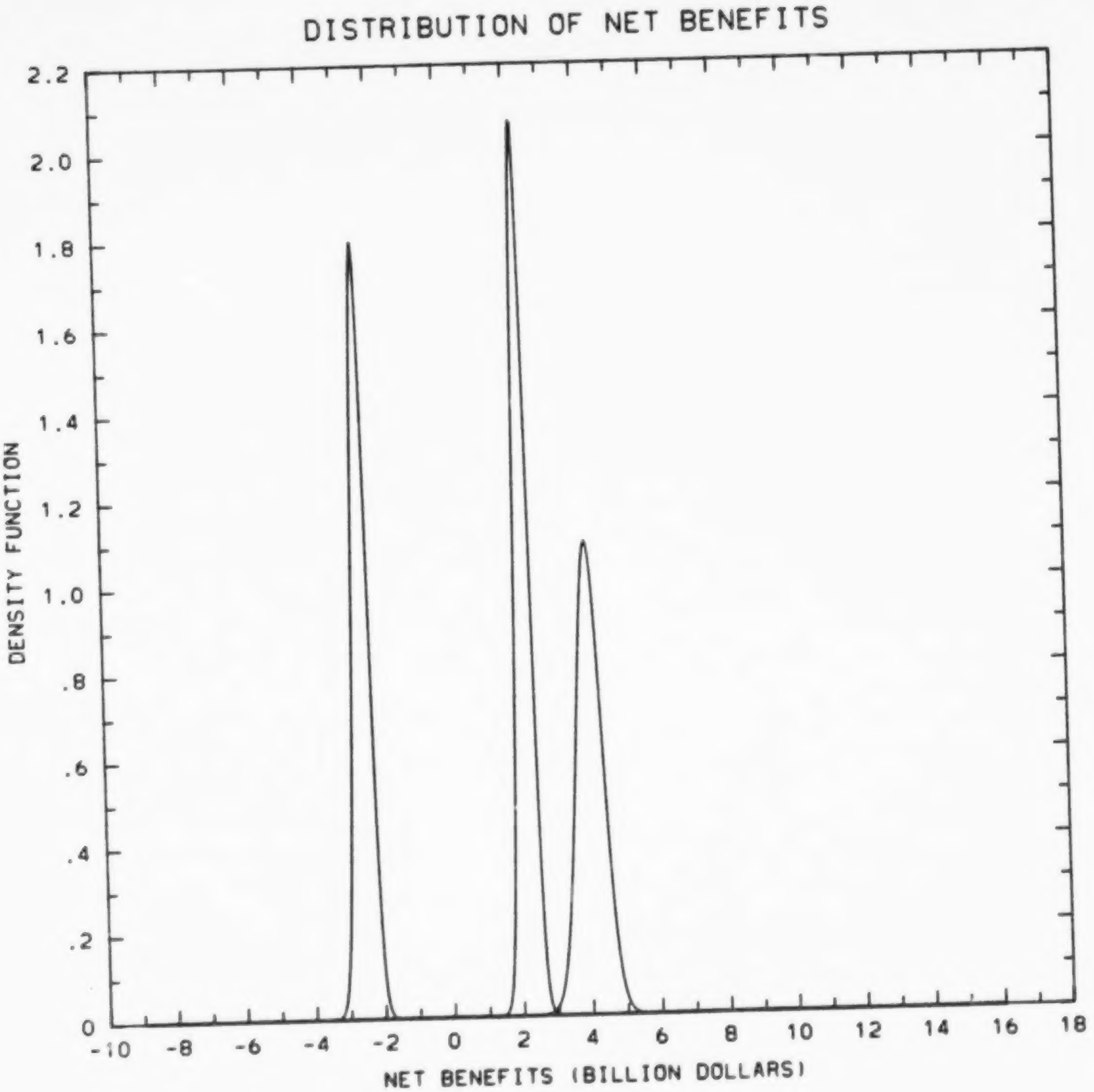

Figure 5.3.1. Aggregate density function for four crops using a quadratic response model.

concerns over initial sample size (beyond the sample size employed in the NCLAN experiments). If more observations are to be acquired, they should perhaps be directed towards broader coverage of a response surface to better discriminate among models, rather than replication of existing dose levels.

A number of caveats need to be noted. The treatment here employed only linear and quadratic yield response functions. The issue of model uncertainty has thus been only partially addressed and the effects of extrapolation across cultivars, regions, and years are not considered. The quadratic model in this analysis did provide for some substantial response differences, particularly for corn. As was noted in Subsection 5.3.2, the use of the Weibull model also results in somewhat different predicted responses at constant O_3 levels, reinforcing the importance of model specification. If the researcher is to use certain other nonlinear yield response functions, which are more consumptive of degrees of freedom than are these forms, this would require perhaps larger sample sizes.

5.3.5 Sensitivity Analysis and the Preliminary 1984 Assessment

The results from 1982-83 economic research indicate that assessments of benefits of pollution control can be estimated from current data with slight to moderate levels of variability in those estimates. It should be noted that these sources of variability are limited to issues of sample size and functional form. Other sources may add to the potential variability in estimates. In statistically-based studies, the variability or range of economic estimates due to uncertainty arising from sample size was approximately 25% and that due to a combination of sample size and functional form approached 60 percent. However, the direction of the effect of model uncertainty was consistent across all air quality assumptions. That is, one model (the Weibull) consistently predicted lower losses. This indicates that any comparisons of different net benefit levels across alternative air quality levels will not change. Hence, any rank ordering of benefits or losses across assumed O_3 levels will not change. These absolute differences in economic benefit estimates will be critical only in a strict benefit-cost context where costs (of control) are assumed to be very close to benefits.

The preliminary national assessment will not be based on statistical procedures. The national economic model will use a series of state or sub-state programming models portraying farm-level crop production, which are then aggregated into a national or macro-level model. This model will be analytically and computationally quite similar to the model used in the 1982-83 Corn Belt regional analysis reported in McCarl et al. (1983) and Adams and McCarl (1983). To test the sensitivity of this model to uncertainty in the dose-response information, detailed sensitivity analyses were performed on the Corn Belt analysis and are reported in Adams and McCarl (1983). These analyses represent the maximum variability due to such sources as extrapolation across cultivars, misspecification of model form, effects of soil moisture stress, and incorrect air quality data as present in current NCLAN data. By taking extreme cases of each analysis, one can bound the range of probable economic sensitivity to the dose-response information. This sensitivity analysis on a large scale model indicates those areas of biological input which have potentially the greatest effect on the economic analysis. This information then provides guidance on areas in need of further or more detailed biological research if economic analyses are to be improved.

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